SOME TEMPORAL ASPECTS OF BINOCULAR VISION.

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by

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ABSTRACT.

An electronic system was designed and constructed to display random dot stereograms, both of the stationary and of the dynamic type. Binocular disparity, the shape of the stereoscopic stimulus and the dot size were easily varied. A further feature was the insertion of a variable phase difference between the two parts of the stereoscopic pair to facilitate tests on the effect of interocular delay. Experiments were conducted, presenting the random dot stimuli for brief periods to subjects and varying the size, shape, position and depth of the stereoscopic stimuli, in order to test some proposed theories of stereopsis. In particular, the Julesz dipole model was found to be useful but not sufficient to explain the results.

A Pulfrich stereophenomenon using only random dot patterns was investigated. A further experiment with non-simultaneous presentation of random dot patterns suggested that the time constant of the binocular fusion process did not vary with the amount of interocular delay.

CONTENTS

	Page
ABSTRACT	2
CONTENTS	3
LIST OF SYMBOLS AND ABBREVIATIONS	6
ACKNOWLEDGEMENTS	8
CHAPTER 1. INTRODUCTION	9
CHAPTER 2. FUNDAMENTALS OF BINOCULAR VISION	18
2.1 Early Psychophysical Investigations	18
2.2 Secondary Cues in the Perception of Depth	22
2.3 Duration of Exposure and the Stereoscopic Threshold	25
2.4 Non-Simultaneous Binocular Stimulation	27
2.5 Neurophysiological Basis for Binocular Vision	30
2.6 Other Topics in Binocular Vision	35
CHAPTER 3. RANDOM DOT STEREOGRAMS	41
3.1 The Construction of a Random Dot Stereo Pair	41
3.2 The Uses of Random Dot Stereograms	47
3.3 Further Implications for Stereopsis	52
3.4 Models of Stereopsis	56
CHAPTER 4. THE GENERAL FUNCTION OF THE APPARATUS	63
4.1 Introduction	63
4.2 The Viewing System	64
4.3 Generation of Random Dot Stereograms	66
4.4 The Use of Pseudo-Random Noise	69
4.5 The Television Equipment	73
4.6 The Stereoscopic Stimulus	74
4.7 The Fixation Point	79

	Page
CHAPTER 5. CIRCUIT DETAILS	94
5.1 The Sequence Generator	94
5.2 The Shape of the Stereoscopic Stimulus	95
5.3 Timing the Stimulus	97
5.4 Implementation of Interocular Delay	98
5.5 The Fixation Point	102
CHAPTER 6. PRELIMINARY EXPERIMENTS	115
6.1 Introduction	115
6.2 Experiment 1	117
6.3 Experiment 2	119
6.4 Experiment 3&4	121
6.5 Experiment 5&6	123
6.6 Conclusion	124
CHAPTER 7. EXPERIMENTS 7-11	136
7.1 Introduction	136
7.2 Experiments 7,8&9	138
7.3 Experiments 10&11	144
7.4 Conclusion	146
CHAPTER 8. EXPERIMENTS WITH INTEROCULAR DELAY	155
8.1 Introduction	155
8.2 Experiment 12	157
8.3 The Pulfrich Stereophenomenon from Random Dot Stereograms with Interocular Delay	164
8.4 A Threshold Experiment with Interocular Delay	172
8.5 Conclusion	181
CHAPTER 9 CONCLUSIONS	190

	Page
APPENDICES	204
A1 PROPERTIES OF PSEUDO-RANDOM SEQUENCES	204
A1.A Introduction	204
A1.B Length of Sequence	204
A1.C The "Shift and Add" Property	205
A1.D The Autocorrelation Function	206
A1.E The Power Spectrum	207
A2 BINOCULAR CORRELATION AND INTEROCULAR DELAY	211
A2.A Variance of the Mean of Two Variables When a Finite Correlation Exists Between Them	211
A2.B Low Pass Filtering of White Noise	211
A2.C Correlation Coefficient as a Function of Filter Characteristics and Interocular Delay	212
A3 A VIDEO SAMPLING SYSTEM WITH INTEROCULAR DELAY	214
BIBLIOGRAPHY	218

LIST OF SYMBOLS AND ABBREVIATIONS

R.E.	Right eye
L.E.	Left eye
L.G.N.	Lateral geniculate nucleus
LC	Inductor capacitor (network)
RC	Resistor capacitor (network)
d.c.	Direct current
sync.	Synchronism
$\delta(t)$	Impulse function
$h(t)$	Impulse response of filter
$H(j\omega)$	Fourier transform of $h(t)$
$n(t)$	Noise waveform
$\bar{X}$	Mean
$\bar{X}_k$	Mean of k^{th} treatment
$S_{\bar{x}}$	Standard deviation of mean $\bar{X}$
σ^2	Variance
F	Ratio of two mean squares in the Analysis of Variance
M_{ST}	Treatment mean square
M_{WT}	Within treatment mean square
df	Degrees of freedom
α	Variable in Duncan's Multiple Range test such that protection level= $(1-\alpha)^{k-1}$ where k is the number of treatments
Φ	Correlation coefficient
ρ	Normalised correlation coefficient
a	Retinal time constant
b	Binocular time constant
b_0	" " " with zero interocular delay
b_T	" " " with interocular delay T

$\hat{\mathcal{E}}$	Change in the stimulus level necessary for detection as interocular delay varies from 0 to T
N	Number of stages in the feedback shift register
$L=2^N-1$	Maximum length of sequence obtained from feedback shift register with N stages
m-sequence	A maximal-length sequence
$a_0, a_1, a_2 .. a_L$	m-sequence of logical 0's and 1's
$b_0, b_1, b_2 .. b_L$	m-sequence of -1's and +1's voltage levels
$\oplus$	modulo-2 addition
p.r.g.	Pseudo-random sequence generator
$R(\tau)$	Autocorrelation function of an m-sequence
$F(\omega)$	Power spectrum of an m-sequence

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CHAPTER 1.

INTRODUCTION.

The human visual system contains two eyes in the front of the head. The visual field which are imaged by each eye lens on their respective retinae overlap to a great extent. From these two retinal images the brain forms one impression of the world. Under certain conditions the brain gets a better impression of an object imaged on both retinae than of a similar object imaged on only one (FOX & BLAKE, 1973). In this situation each eye samples the world and the brain makes a more reliable judgement from two samples than from one. When evidence from one sample contradicts that obtained from the other the brain is forced to make a choice. The eye that the brain chooses to accept as giving the correct view is called the dominant eye. Eye dominance varies from one observer to the next in both type and degree and may also vary across the visual field for one observer. When an observer pays attention to some point in space that is clearly visible in both eyes, the eyes converge so that the image of this point falls on the fovea of each retina. The fovea is the centre of each retina and is the region of highest visual acuity so that when attention is paid to an object in space, the eyes move so as to give the brain the most exact description of the object. Other objects near to the point of fixation (where interest is directed) are also imaged by each eye and so the three-dimensional world is mapped onto the two-dimensional retinae. The brain is able to reconstruct an impression of three dimensional space because of the slight differences in the relative positions of the objects' images in the two retinae. By a comparison of the two retinal images each object seen by the observer may be located in depth relative to the point of fixation. The study of binocular vision may be divided

into the three topics mentioned above. Firstly there is binocular summation of subliminal monocular images, where two eyes may be used to obtain a better judgement than one alone. Secondly there is the study of binocular rivalry where two retinal images are incompatible and cannot be fused. Binocular rivalry is frequently used as a tool in psychological research. Finally there is the study of the spatial localisation of objects in space through binocular vision. There are many binocular cues the brain may use to locate objects in space and these are listed in section 2.2. but the most important cue is the relative horizontal disparity of retinal images. The use of this cue is called stereopsis.

Most of the experiments reported in this thesis concern the last topic. Stereopsis under brief exposures is investigated in the centre of the visual field. In addition an experiment is performed on stimulus masking with visual noise when the noise but not the stimulus is subjected to an interocular delay. This falls within the first topic of binocular summation. Interocular delay in effect, means that an optical delay line is placed between the stimulus and one eye. Thus one eye lags behind the other. The use of interaural delay as a tool to study binaural fusion is more familiar than the binocular equivalent even though Sherrington (SHERRINGTON 1906) employed it more than seventy years ago in a study of critical fusion frequencies. Interaural delay is important in binaural fusion because the time delay between the audio signal reaching each ear gives information about the location of the sound source and is therefore analogus to binocular disparity rather than interocular delay. Interaural delay occurs naturally but interocular delay may only occur if the retinal luminance is unequal in the two eyes. Luminance affects the speed of response of the retina to light sources. An optical illusion dependent upon this fact is the Pulfrich stereophenomenon (OGLE, 1962; PULFRICH,1922) where a simple

pendulum appears as a conical pendulum when a neutral density filter is placed over one eye. This and a similar effect with visual noise is fully described in chapter 8. Interaural delay is useful to a listener because of the spatial information it brings and the brain needs some method for appreciating this delay. Interocular delay is not useful to the observer and only serves to distort movement. There is a slight possibility that, if it should occur naturally through unequal retina luminance, the brain is able to adapt itself to minimise the effect upon binocular fusion. This possibility is investigated by an experiment described in Chapter 8.

The human visual system does have some similarities to its aural counterpart. In order to gain a fused image from two receptors nerve fibres from one receptor pass across the brain to meet with fibres from the other receptor. The part of the brain that deals with vision is called the visual cortex. Half of this belongs to the right cerebral hemisphere and the other half to the left. The right hemisphere contains the fused "brain image" of the left visual field whilst the left hemisphere deal with the right visual field. Nerve fibres emanating from each retina are divided into two groups. A vertical line through the fovea divides the nasal hemi-retina from the temporal hemi-retina and hence the left visual field from the right visual field. Fibres from the nasal hemi-retina of one eye cross over the brain to meet with fibres from the temporal hemi-retina of the other eye. If this division were absolute then an object immediately in front (behind) of the fixation point would stimulate points on two temporal (nasal) hemi-retinae and binocular fusion would be impossible. However, stereopsis in the centre of the visual field is possible except in subjects with split brains (MITCHELL & BLAKEMORE, 1970). This indicates that inter-cerebral communication is an important factor in maintaining stereopsis over the entire visual field.

It has been found that limits in the extent of intercerebral communication result in a drop in the accuracy of locating objects very far in front or behind the observer's point of fixation (BLAKEMORE, 1970).

Physiological research in the last decade on the visual system of cat and monkey have tended to reveal neural units in the visual cortex which respond to a particular set of stimulus conditions. Typically these could be a moving edge (formed by bright gradients) aligned at a certain angle (HUBEL & WIESEL, 1962) or a binocular stimulus at a certain disparity (BARLOW et al, 1967). A neural unit that optimally fires for one set of stimulus conditions is inhibited by an unpreferred set. The author has performed psychophysical experiments on stereopsis in the centre of the visual field with a view to relating the results to the ideas of intercerebral communication and the characteristics of specific neural units discovered by recent physiological research. Use was also made of a physical analogy to the brain's mechanism of stereopsis suggested by Julesz (JULESZ, 1971).

Physiological research, of the type necessary to probe the neural equivalent of the visual image, may only be carried out on animals. The cat and monkey are thought to possess a binocular visual system similar to man but ideas thrown up by such research must always be tested by psychophysical experiments on normal human subjects before the neurophysiological findings can be carried over confidently to man. With greater neurophysiological knowledge on the brain's visual system now available there is less need for simple physical models to describe a particular action or function of the brain. However, although neural functions at the first stages of the analysis of the retinal image may be isolated, it is not yet possible to provide a general neurophysiolcgical description for the chain of events leading to the observer's decision as to the nature of the visual stimulus.

There is then a place for the physical analogy which adequately describes the results of phychophysical experiments even though the analogy itself may seem very far from neurophysiology. The physical analogy of Julesz possesses inertia and therefore lends itself very well to describing temporal aspects of stereopsis.

Special stereoscopic stimuli were used in all the experiments reported in this thesis. They are called a random dot stereograms, invented over a decade ago (JULESZ, 1960) and now seeing extensive use in studies of stereopsis as well as psychological research in quite different fields (section 3.2). The random dot stereogram may be seen as a method of displaying a figure distinct from its background using only the depth cue of binocular disparity, without any brightness gradients or any familiarity cues defining the boundaries of the figure. In monocular viewing the eye sees a matrix, each point of which being assigned a brightness level in a random manner. The boundaries of the figure cannot be discerned from this random texture but after binocular fusion the matrix separates into two depth planes. The fact that most observers see this separation demonstrates that stereopsis is possible without any familiarity cues. This discovery anticipated the neurophysiological finding that disparity-specific binocular cells exist in the visual cortex for without these disparity-specific units stereopsis ffom random dot stereograms would be a difficult task for the brain. Because the random dot stereogram isolates the binocularity disparity cue it is the ideal stimulus to probe the brain's system of binocular fusion arrays of disparity-specific units.

For an N by N square matrix with two brightness levels allowed, there are 2^{N^2} different dot patterns. Each one may be used with its stereoscopic complement to present the same figure at the same depth relative to its background or reference plane of dots. Alternatively the 2^{N^2} dot patterns

may be presented in rapid temporal succession so that in monocular viewing the observer sees the dots in rapid random motion as in the visual noise that may be observed in an untuned television receiver. In binocular viewing of this dynamic random dot stereogram, the figure stands distinct from its background and is made up of a texture of visual noise. Use is made of dynamic stereograms in the experiments on interocular delay reported in chapter 8.

A special electronic device was constructed to generate and display the stereograms. This device is fully described in chapters 4 and 5 but briefly its facilities included variation in position, shape and depth of figure and interocular delay. The density of dots was large enough for small figures to be presented in the centre of the visual field.

The physiology and psychology of speech and hearing have long been of interest to communications engineers. Corresponding interest in visual perception has been more recent but is becoming increasingly more important as solid state technology continues to be developed. Large scale integration in MOS technology will allow more complex signal processing to take place in a terminal receiver so that ambitions bandwidth compression schemes may be attempted without making the consumer's equipment too bulky or expensive. Development of solid state displays will allow possibilities in scanning techniques not feasible with the familiar cathode ray tube display. Communications engineers will always need to know about the perception of humans when they are at either end of a communication link. It is wasteful to use excess channel capacity to ensure perfect transmission of a signal when a certain amount of degradation cannot be detected by the observer. When the characteristics of the perceptual process are known it will be possible to code signals (speech or vision) efficiently so that, after distortion and degradation by noise in the channel, the decoding at the

terminal will adequately and unambiguously stimulate the human receiver.

The ordinary cathode ray tube display makes use of certain basic properties of the human visual system. For example, the field repetition frequency of 50 HZ (60 HZ in North America) matches the response of the retina. If the video signal is noise-free, then scanning at 200 HZ does not give the viewer a better picture. The finer resolution of movement cannot be appreciated because of the slow response of the retina but if noise is added to the video signal a subjective improvement in the signal ratio would be obtained. With the field frequency fixed the necessary video bandwidth is related to the limits of resolution of the eye. The viewer does not wish to see the scanning lines nor does he wish to see an "out of focus" picture. The design of the cathode ray tube display is related to the properties of the peripheral processes of the visual system and not to the central processes at the visual cortex. Whether it is possible to make use of some of the complex functions of the visual cortex in designing more efficient televisual systems is an interesting engineering problem but one that is touched only indirectly in this thesis. However, neurophysiological evidence indicates that binocular fusion is a primary function of the visual cortex and stereopsis, which results from binocular fusion, is investigated in the experiments reported in this thesis as is binocular interaction with interocular delay. Some comment can therefore be made on the engineering importance of binocular fusion as a primary function of the visual cortex.

Three dimensional displays may have some importance when a two dimensional representation is confusing or inadequate. This may occur for an unfamiliar object such as a model of complex molecular structure in organic chemistry (ORTONY, 1970) or a graphical representation of a mathematical function of three variables (JULESZ & MILLER, 1962). It is unlikely to be

developed for or ordinary television broadcasting as experience in the film industry suggests that its value in entertainment is not great. However, there is a possibility that binocular summation of heavily noise degraded or subliminal stimuli could be important for special purposes. An application of the reaction of the visual system to interocular delay is described in Appendix 3 though for reasons given in chapter 8 and 9 this will never be very useful.

The contribution of the work described in this thesis to the study of binocular fusion is primarily the development of a special device to display random dot stereograms and in particular dynamic stereograms with interocular delay. The great density of dots in the displayed patterns have enabled experiments to be conducted with small stimuli so that the limitations of stereopsis in the centre of the visual field, which has previously been studied with classical line images, may be repeated with Julesz patterns. The novel method of tachistoscopically presenting stereoscopic stimuli with interocular delay used in Experiment 12 and described in section 8.2 could be of future use to workers in this field.

The Pulfrich stereo-phenomenon using only random dots has not been reported previously and reasons for this are suggested in section 8.3. Although it is known that a $\sqrt{2}$ improvement in the picture signal to noise ratio can be achieved by masking each eye's stimulus with independent noise sources, the author is not aware of any experiments reported on the application of masking noise with interocular delay. In this respect Experiment 13 (section 8.4) is original although it is not suggested it is a good method for the estimation of the stereoscopic summation time.

Chapter 2 briefly reviews the early work on binocular fusion by the scientists such as Helmholtz, Hering and Panum. Stereopsis as a cue to depth is put into perspective by a list of the secondary cues to spatial

localisation of objects in space. Tachistoscopic and non-simultaneous presentation of stereoscopic stimuli is discussed and the physiological basis for binocular fusion is outlined. Chapter 3 is devoted to the perception of random dot stereograms. A complete description of their construction is given and the perception of the"ambiguous areas" fully discussed. The author compares some findings of his own with those of Julesz and reviews the role of random dot stereograms in perception research. Chapters 4 and 5 describe the author's apparatus, the latter chapter describing the electronic circuits involved whilst the former is a general account of the experimental methods used in the author's research. Chapters 6, 7 and 8 report the experimental work with chapter 8 devoted to experiments with interocular delay and chapters 6 and 7 concerned with experiments involving stereopsis in the centre of the visual field and other general experiments. Chapter 9 concludes the thesis with a discussion of the implications of the research undertaken.

CHAPTER 2

FUNDAMENTALS OF BINOCULAR VISION.

2.1. EARLY PSYCHOPHYSICAL INVESTIGATIONS.

Although the subject of binocular vision took the attention of both Newton and Descartes, significant interest only developed after Wheatstone's invention of the stereoscope in 1838 (Fig.2.1). Panum was the first scientist to devote considerable time to the study of binocular fusion and von Helmholtz paid particular attention to binocular fusion in his "Handbuch der Physiologischen Optik".

Panum noted that if the eyes are fixated on some point, then objects placed near this fixation point are seen as single objects (through fusion of the binocular images) whereas objects much closer or further away from the observer are seen double. The area around the fixation point where objects are seen single is known as the Panum fusional area. Figure 2.2 demonstrates this and shows how the width of the fusional area increases with the peripheral angle in the visual field.

A distinction must be drawn between the "actual objective physical world of objects and the subjective visual world as experienced by the person " (OGLE , 1962). When an eye fixates on an object, the image of this object on the retina is located on the fovea. The subjective direction of the object from the observer is termed the principle visual direction. It would appear that if both eyes fixated on a single point of fixation there would be two principle visual directions (Fig.2.3) but Hering showed that the two directions were identical. This fact is known as the "law of identical visual directions". Hering's famous experiment is as follows. The observer stands two feet from a window that affords a good view. He closes his right eye and directs his left to a point on a

distant object somewhat to the right and makes a mark on the window in line with his left eye and the fixated point. He then closes his left and opens his right and notes which object is in line with the mark and his right eye. Opening both eyes and directing them to the mark on the pane the two objects are seen in one visual direction - the same as the mark, although in objective space the two objects may be widely separated.

From the definition of the principle visual direction comes the notion of corresponding retinal points. With the eyes directed to some fixation point there must exist for every retinal element in one eye a corresponding one in the other which gives rise to the same subjective direction. These elements are termed corresponding retinal elements and may be mapped out by Volkmann's "Nonius" method (OGLE , 1962). Subjective directions are always relative to the principle visual direction associated with a fixation-point image on the fovea. Absolute visual directions which enable the observer to orientate himself in his environment involve processes in addition to the signs obtained from retinal stimulation. Visual direction of objects in space remain stable despite eye movements and changes in fixation point. This stability is thought to be due to nerve signals which lead to eye movements providing the information for overall corrective directional sense.

Apart from the Hering experiment there are many descrepancies between subjective and objective space. When asked to divide a horizontal line observers may consistently overestimate the size of the temporal half (KUNDT partition) or conversely the nasal half (MUNSTERBERG partition) Lines adjusted to appear vertical may actually be rotated temporally at the top by one or two degrees from the true vertical and indeed there are many other examples of objective - subjective discrepancies in the field of optical illusions.

Returning to the problem of fusion Fig.2.4. illustrates the situation where the eyes are directed to a fixation point and another object is present inside the Panum fusional area and is therefore perceived as a single object. In general, the images of this object will not fall on corresponding points on the two retinas and therefore there exists two subjective visual directions associated with the object yet it is perceived single. This is one of the classical problems of binocular fusion.

An old theory proposed to account for the phenomenon of Panum's fusional area is that rapid mystagmoid movements (movements unsynchronised in the two eyes) somehow average out the effect of two subjective directions. Verhoeff proposed a replacement process in which portions of the images were seen alternately by one eye and then by the other. LeGrand suggested that Panum's areas are the result of a lack of acuity in the perception of double images of vertical rods or threads. It is now thought more likely that a cortical process, possibly involving pattern recognition of the retinal images at some level, arranges for a final composite "image" in the brain to be obtained.

If the images of the object P in Fig.2.4. had fallen on corresponding retinal points the object would have been, by definition on the longitudinal horopter for that particular fixation point. Objects lying on the horopter are perceived at the same distance from the observer as the fixation point. Consider the case where a point object is moved off the horopter in the principle visual plane, so that the image on the left retina remains fixes whereas the right image is shifted transversely across the right retina. The distance the latter image moves is known as the binocular disparity for that object with respect to the given fixation point. The object is no longer perceived at the same distance from the

observer. If the object has not moved out of Panum's fusional areas it will be seen singly. The information about the relative depth between the object and the fixation point is in the binocular disparity. The perception of depth by the comparison of disparate images is called stereopsis.

If points on the retinas of the two eyes which are at equal lateral distances from their respective foveas are actual corresponding points then the longitudinal horopter is the Vieth-Muller circle (Fig.2.5). In fact the true horopter, by whatever method it is determined never lies on this circle but somewhere between it and the objective frontoparallel plane. The deviation of the true curve from the Vieth-Muller circle has been called the Hering-Hillebrand horopter deviation. The point P in Fig.2.5. stimulates a point in the temporal hemi-retina of the left eye and a point in the nasal hemi-retina of the right eye. Since P is not on the Vieth-Muller circle the angles θ and ϕ are not equal. Hillebrand suggested that this result indicates an asymmetrical spatial distribution of corresponding points on the retinas and this is supported by the monocular partition experiments of Kundt and Munsterberg already mentioned.

An object in Panum's area is seen both singly and in depth with respect to the fixation point. Outside Panum's area the experience of depth may still be compelling though two objects are seen. At larger disparaties a qualitative response of "nearer" or "further" may only be experienced and a further increase in disparaty may destroy the depth effect and the two half images become indefinitely localised.

Binocular disparity alone yields stereopsis but there is evidence that secondary cues, both monocular and binocular, aid in the spatial localisation of objects and possibly in the compulsion for fusion itself.

These are described in the next section.

2.2. SECONDARY CUES IN THE PERCEPTION OF DEPTH.

Stereopsis may be the principle mechanism for the determination of depth but normally there exist numerous secondary cues that the observer may make use of. Most of these cues are available in the monocular image but some are exclusively binocular. The importance of monocular cues to spatial localisation of objects may be judged by the apparent ease with which a one-eyed man pursues a normal life.

The retinal image that an object gives rise to is proportional to its size and inversely proportional to its distance from the observer. This relationship between size and distance is embodied in what is called linear perspective. It is thought to be a very powerful cue to the estimation of distance and is sometimes used to explain optical illusions such as the Ponzo illusion (GREGORY, 1970). It has been shown (HOLWAY & BORING, 1941) that when judgements are made of the size of objects at different distances the observer will adjust the size of the test object to the actual size of the reference object. The observer is better at this the greater the number of visual cues present which will help him to estimate the different distances. With visual cues reduced as far as possible size judgement seems to depend only on retinal size of image. The fact that apparent size remains constant regardless of apparent distance is normally called the size-constancy phenomenon and it was first expressed in Emmert's law which gives the rule for the estimation of the size of after-images superimposed on surfaces at different distances from the observer.

The loss of discrimination of details in a figure and therefore of

surface texture with increasing distance from the observer is a cue to this distance. A texture with a repetitive pattern gives a cue to distance when slanted with respect to the visual axis. The aid that such vertical gradients give to depth perception has been studied by Gibson (GIBSON,1950). The shape constancy of solid objects may also be considered a depth cue. An object such as a plate on a table is known to be circular yet it gives an elliptical image. The upper boundary of the ellipse is then taken to be further from the observer than the lower boundary.

Interposition is a most useful cue to relative depth localisation. A near object in the same line of sight from the observer as a distant object prevents the formation of a complete image of the latter. The use of this cue rests upon the recognition by the observer of the discontinuity of the boundary of the distant object and is thus linked with gestalt organisation.

The loss of sharpness of contours may lead to an experience of greater distance from the observer. This may be due to limit of resolution in the visual system or due to the properties of the medium through which light passes. Water vapour, dust, and smoke particles in the atmosphere blur the outlines of distant objects, making their details less distinct. Their hues also become less saturated as they are further away from the observer. The atmospheric medium is also spectrally selective so that distant object appear bluer and nearer objects redder. This is quite apart from the effect of chromatic observation of the eye lens that causes, in darkness, point sources of blue light to appear further away than point sources of red light.

Brighter objects are generally taken as nearer than darker objects. The pattern of shading on a surface is a very strong cue to depth as is

suggested by the fact that when a convex surface is illuminated from below (illumination in common experience comes from above) it appears concave.

When the head moves but objects in space are stationary the images of these objects move across the retina. Images of near objects are subject to greater translation than distant objects and thus appear to move faster. This cue to depth is called motion parallax.

Because the eyes are above the ground objects further away from the observer on flat ground form images lower on the retina (higher before inversion) than those that are nearer the observer. This is a useful cue in pictorial representation.

A further monocular cue may be found in a proprioceptive sense of accommodation of the eye lens but it is not known to what extent if any this is used. A binocular proprioceptive cue could exist in the differing amounts of accomodation required for focusing on an object of different distances from the two eyes or from a sense of the angle of convergence at fixation.

A many faced solid object, such as a cube, close to an observer may present quite different aspects to the two eyes. This aspect difference may serve as a secondary binocular cue to spatial localisation. It would probably be of greater use for familiar objects.

Vertical disparity may serve as a depth cue for an object viewed in asymmetrical convergence. The different distances of the object from the two eyes would yield images of different sizes. These differences decrease as the object is placed further away from the observer.

A repetitive pattern in the fronto-parallel plane, such as a wall-paper of vertical stripes produces an image on the retina with a periodic

spacing that is distorted since the stripes are at different distances from the eye. The second eye in a different viewing position receives a retinal image containing different distortions. Again these differences decrease as the fronto-parallel plane is moved further from the observer.

Binocular difference in interposition is a cue related to aspect difference. The overlap between an image of a near object and the image of a far object may be quite different for the two eyes (Fig.2.3).

2.3. DURATION OF EXPOSURE AND THE STEREOSCOPIC THRESHOLD.

Dove (DOVE,1841) discovered that depth could be perceived from line drawings in a stereoscope illuminated for a very short time by an electric spark. Hering (HERING, 1865) confirmed this result with his famous falling bead experiment. In this experiment the observer viewed a plumb line through a horizontal slit whilst a bead was dropped either in front or behind the line. Subjects were able to perceive depth in this situation quite well even though secondary cues were minimal and the bead was seen for a very short time. Smith (SMITH,1946) confirmed substantially the same results which imply that neither convergence movements of the eyes nor proprioceptive influences from the external muscles of the eye are necessary for the emergence of a stereoscopic perception of depth.

Langlands (LANGLAND, 1926) examined the stereoscopic threshold under conditions of short exposure and although his experimental apparatus and procedure has been criticised (OGLE,1962) his results are summarised as follows. For an exposure time of greater than three seconds there existed a constant low threshold of stereoscopic depth. When the exposure

time decreased from three seconds to 1/10 second the stereo threshold increased. As the exposure duration decreased further the stereo threshold became constant. The threshold of stereoscopic depth perception under a given set of conditions is defined as the least difference in sagittal distance between two objects that can be discriminated.

Ogle criticised Langland's experiments because he claimed that the stereoscopic threshold was not measured under the same condition for all exposure times. He pointed out that at short exposure times little light energy falls on the retina and since it is known that the level of illumination affects the stereoscopic threshold it is necessary to account for this in the experimental procedure. Stereopsis is possible at scotopic light levels but the threshold decreases rapidly as the overall illumination increases. At high photopic light levels the stereoscopic threshold becomes a constant low value.

In an experiment (OGLE & WEIL, 1958) which was based on Langland's original experiment but with all the parameters that were known to affect stereopsis kept constant the results shown in Fig. 2.6. were obtained. An explanation for these results can be forwarded on the basis of normal physiological ocular nystagmoid movements . There are two types of movement. The first are small binocularly uncorrelated movements with a maximum frequency of about 100HZ and a median extent of 15 secs of arc which probably play no part in visual perception. Secondly there exist large involuntary drifts and jerky motions of the eyes which are equal and synchronised together. Nystagmoid movements have long been cited to explain the extraordinary high visual acuity that the eye appears to have. Stereopsis is related to visual acuity since to get a true qualitative sense of depth the binocular disparity must be

accurately evaluated. As the exposure duration decreases, the extent to which the eye can move is reduced. For very short exposures the retinal image is stopped and an upper boundary for the stereo threshold of perception is reached.

2.4. NON-SIMULTANEOUS BINOCULAR STIMULATION.

Guilloz noted in 1904 (translation (OGLE, 1962)) that "when the two eyes are open and seeing alternately, never at the same time, but with a very much reduced period of total occlusion all sensation of relief is as perfect as in the direct observation of the objects....
These experiments show how the perfect sensation of stereoscopic relief can depend continually super-additive judgements although having been formed with the aid of successive impressions of which physiologically one is already erased or almost so when the other acts".

Ogle could not verify the existence of stereo depth perception with after-images imprinted first in one eye and then in the other but succeeded in getting depth from after images simultaneously imprinted.

A good deal of experimental work has been done on a problem very similar to non-simultaneous presentation of images to the two retinas. This is the modification of Hering's falling bead test where one eye sees only the top half of the fall and the other sees the bottom half of the fall. Thus the eyes do not see the falling bead simultaneously. This experiment (VAN DER MEULEN & VAN DOOREWAAL, 1873) was performed by taking the Hering apparatus and placing an optical prism in front of one eye. They concluded that as depth was seen, the depth finding process was a

psychicalone as opposed to a physiological one. Hofmann, by qualifying the word psychical, said (translation (OGLE, 1962)) that "we should always have to classify binocular depth perception among the gestalt perceptions" after he had performed the same experiment. Ogle did the Hering falling bead test with more elaborate apparatus and found that though a stereo response was certainly present when individual eyes saw different parts of the bead's fall the effect was not a true quantitative stereopsis but only a weak sense of further or nearer than the fixation point. He concluded that for true stereopsis the simultaneous stimulation of horizontally associated disparate elements is necessary. (OGLE, 1954).

Efron performed an interesting experiment (EFRON, 1957) in which the constituents of a stereo pair were presented non-simultaneously to the two eyes. Non-simultaneous presentation was facilitated by a rotating disc with adjustable viewing slits cut away. The stereo image consisted of a sequence of three letters each letter placed in space at a random sagittal distance from the observer who had to perceive the relative depths in the sequence. The experimental variables were; -

I) SHORT INTERVAL (SI)

This is the time between the end of stimulation to the first eye and the start of stimulation to the second eye

II) LONG INTERVAL (LI)

This is the time between the end of the stimulus to the second eye and the start of the stimulus to the first eye

III) FLASH DURATION

This is the time allowed for each eye to view its half of the stereo pair

IV) INTENSITY OF ILLUMINATION

Efron found that, with the wheel set in motion, horizontal flicker

was perceived. At this stage the subject was unable to say which letter was nearest. The first letter to become fused and be located in space, as the disc was turned faster, was the nearest. This was soon followed by the other two. If the wheel speed was then reduced the subject could often still hold the letters in position. This hysteresis effect seems to be a feature of stereoscopic vision and is to be compared with hysteresis observed when stereo images are pulled apart in stabilised vision (FENDER & JULESZ, 1967) which is described in the next chapter. In Efron's experiment a meaningful word was fused more readily than a nonsense sequence.

More objectively he found that the ratio LI/SI had the greatest effect in determining the maximum permissible time between stimulation of one eye and the other. The longer the interval between the flashes presented to one eye, then the shorter the interval between the stimulation of each eye. The limiting value for the short interval was 13 milliseconds and occurred when only one couplet was presented (i.e. long interval was infinite).

Efron concluded that a temporal summation of images had occurred and asked the question of whether this occurred as a function of retinal persistence or as a result of a more complex process in the visual cortex. He postulated the latter by appeal to the fact that the flicker fusion threshold and the stereoscopic fusion threshold were clearly distinct.

Dodwell and Engels did the same experiment replacing Efron's wheel with electronic flashlights and found substantially the same results (DODWELL & ENGELS, 1963). They proposed a simple cell network model to explain them. Noting the discovery of binocular disparity cells in the visual cortex (HUBEL & WIESEL, 1962) they proposed that the strength of the electrical signal delivered by these units depended upon the degree

of overlap between the left and right eye signals. The binocular pulse was expanded temporally according to its initial strength and had to last until the production of another binocular pulse. Therefore as the short interval of Efron's was increased the binocular pulse became weaker and the long interval had to be made shorter to enable fusion to take place. It will be noted that there is no provision for hysteretic effects in this model.

2.5. NEUROPHYSIOLOGICAL BASIS FOR BINOCULAR VISION.

It is well known that, in man, a partial decussation of optic fibres exists (Fig.2.7) such that the ipsilateral fibres from the temporal hemi-retina and the contrlateral fibres from the nasal hemi-retina come together in an optic tract. There are thus two optic tracts, one in each cerebral hemisphere. The left sided optic tract carries signals from both eyes referring to the right hand field of view whilst the optic tract on the right side of the brain deals with the left half of the visual field. The optic tracts each run into a lateral geniculate nucleus which acts as a relay station for the nerve impulses and thence to opposite sides of the visual cortex. At what point in the brain stereopsis occurs has always been a difficult problem but recent findings in neurophysiology have clarified the issue considerably.

It was formerly thought that visual form is first elaborated for each eye separately and that stereopsis is added in the brain after all analysis on the monocular stimuli is completed (HELMHOLTZ, 1909). Work on stereopsis with random dot stereograms cast doubt on this even though it was found (JULESZ, 1960) that monocular cues superimposed on the random dot stimuli greatly facilitated stereopsis. However the discovery (HUBEL & WIESEL, 1962, 1968) that many cells in the visual cortex of the cat and monkey

are binocularly driven and that these binocular cells precede in the neural pathways cells whose purpose is to spot complex features provides a neurophysiological basis for an alternative theory.

Neurophysiological research has led to the discovery of many special purpose cells in the visual system. Neural processing or pattern recognition rests upon the inhibitory nature of some inputs to a nerve cell and these were first identified in the visual system of a crab (HARTLINE, 1949). Kuffler (KUFFLER, 1953) introduced the idea of a receptive field. He found that, in fact, retinal ganglion cells could be excited by the illumination of small spots on the retina but inhibited by the stimulation of other areas.The optimum stimulus configuration was a bright spot in a dull ring or a bright ring surrounding a dull centre. Concentric receptive fields similar to this have been found in the lateral geniculate nucleus ot the cat. (WIESEL & HUBEL, 1966). Simple movement detectors in the retina of the rabbit have also been discovered (BARLOW & HILL, 1963). Pattern recognition in the frog's visual system has been studied (LETTVIN et al, 1959) with a view to relating identifiable stimuli to the frog's necessities of life.

After an extensive study of the function of individual cells in the cat's visual cortex, Hubel and Wiesel have proposed the concept of a hierarchical order of visual neurons. Cells with simple stimulus requirements provide the receptive fields for more complex cells.Hubel and Wiesel have suggested the classification of visual neurons into simple, complex, lower-order hypercomplex and higher order hypercomplex (HUBEL & WIESEL, 1968).

Typically simple cells have narrow elongated receptive fields. The flanking areas around these slits may be symmetrical or asymmetrical so that, for example an excitatory slit may be inhibited only on one side. The orientation of the slit has been found to be critical; changing the

orientation by 5° - 10° is often enough to greatly reduce a response or remove it completely. In addition to these detectors there are edge detectors whose receptive fields have excitatory and inhibitory regions meeting at the detectable boundary. Moving stimuli are effective and optimum rates of movement vary from one cell to the next. Complex cortical cells have receptive fields that are not easily mapped out for they respond to a range of variously-shaped stimuli both stationary and moving.

There is a link between cortical organisation and functional organisation in the visual cortex of the cat. A vertical column (perpendicular to the cortical surface) contains many types of cells but all these feature extractors have the same preferred organisation. Also cells having receptive fields in neighbouring retinal images lie close together in the visual cortex.

In Hubel and Wiesel's early work it was assumed that the receptive field and the appropriate stimulus for a particular cortical neurone was identical for each eye and that the signals from the two eyes were added together when the two stimuli were correctly located. It was further assumed that the two stimuli always lay in corresponding regions in the two retinae so that the binocular stimulus was at an effective zero disparity. Later other researchers studied binocular cells and achieved different results (BARLOW, BLAKEMORE, PETTIGREW, 1967). They found in a study of binocularly driven units in the visual cortex that a stimulus located, with the optimum binocular disparity, in the visual fields of both eyes was more effective in driving the units than a monocular stimulus and much more effective than a binocular stimulus which was correctly positioned in only one eye (i.e. at a sub-optimum disparity). The spread of optimum disparities displayed by these binocularly driven units in a cat was about 6.6° for horizontal disparities and about 2.2° for vertical disparities. It is clear that with fixed convergence different

units will be optimally excited by objects located at different sagittal distances. This suggests a basic mechanism depth in the cat. This would be a parallel search process because for a particular object the possible disparities are investigated simultaneously by an ensemble of disparity-specific binocular cells. A single cell may also be selective in its feature extraction so that it may do the two basic parts of the stereopsis process, namely the pairing of images of the same feature and the assessment of binocular disparity. Unfortunately the actual disparities reported by Barlow et al in the above-mentioned publication were not thought by the researchers to be very accurate because of difficulty in locating the area centralis of the cat and they were unable to be very positive about whether or not ther was an association between mean disparity and eccentricity in the field of vision. They also cautioned against carrying over the results obtained from a cat to the visual system of man saying that " the cat, a hunting animal, surveys a wide range of depth at low accuracy, whereas man, a sophisticated toolmaker surveys a narrow band at high accuracy varying the position of the band with his convergence movements".

An important aspect of the input connections for a typical visual neuron is that many of them are wholly inhibitory. The inhibitory mechanism suppresses the activity of the cell whenever stimulus features inappropriate to its specialisation are presented in the receptive field of the unit. A particular small part of the visual field cannot provide appropriate stimuli for more than a small proportion of the cells with receptive fields in the area so that the activity of most of them will be suppressed.

Cortical units looking for particular features maintain a much lower level of discharge than units lower down in the visual pathway

because of the inhibitory effects of inappropriate stimuli.

Most cells in the lateral geniculate nucleus have a binocular influence of an inhibitory nature. There is no excitatory interaction between the two retinal inputs until the visual pathways come together in the visual cortex. (BISHOP, 1970). The specific stimulus property required for the discharge of a binocular cell is very similar for both eyes and the receptive fields have the same size and arrangement. The only difference between the two fields relates to eye dominance (BLAKEMORE & PETTIGREW, 1970).

By examining the responses of many binocular disparity cells Bishop was able to suggest a neural basis for the phenomena of binocular single vision. He found that each binocular cell gave an optimal response when both eyes were appropriately stimulated with the same particular feature and for a particular disparity between the right and left eyes. If the disparity was slightly more or less than this then the cell response was greatly reduced. Furthermore separation gave rise to an increased response but at a lesser strength than the optimal binocular response. This means that a binocular disparity cell only fires at full strength for a particular disparity and an object at a certain distance from a fixation point will only stimulate one set of binocular cells, other sets of slightly different disparities being inhibited. There will be in general four further sets of binocular cells that fire sub-optimally because they are stimulated by the feature in one eye but are not inhibited by the same feature in the other, their particular disparity being much greater or much smaller than the disparity of the actual object. The optimal response of one aggregate of cells indicates the depth. When the object is very far or very near the observer such that the disparity is very great then there may be no cell which fires optimally. Furthermore only

two sets of cells will fire sub-optimally. These give rise to double images which nevertheless still indicate a sense of nearer or further from the fixation point. Thus the classical findings of Panum and others now have a neural explanation.

It was once thought that many of the cells in the visual cortex were exclusively monocular but recent findings have shown (BISHOP, 1970) that in the cat many if not most of these cells have inhibitory and subliminal excitatory response fields from the non-dominant eye. These cells are discharged from a stimulus in one eye if and only if the subliminal excitatory region in the other eye is also stimulated. Bishop calls these cells binocular gate neurons.

2.6. OTHER TOPICS IN BINOCULAR VISION.

An object that lies directly in front or behind the fixation point has its image on temporal or nasal hemi-retinae in both eyes. If there is strict partial decussation of the nerve fibres projecting from the retinae then such an object should be represented monocularly in each cerebral hemisphere. It has been suggested (BLAKEMORE 1969) that an intercortical pathway exists through the corpus collosum (Fig.2.7.) which allows the convergence of the monocular signals onto single binocularly driven neurons. In the cat a central vertical strip in the visual field about the point of fixation is represented in both cerebral hemispheres. It has been shown (BLAKEMORE, 1969) that the size of this bilateral representation accounts quite well for the range of binocular disparities found in neurons in the cat's visual cortex which have receptive fields in the area centralis. This range of binocular disparities is about 2 to 3 degrees in the centre of the visual field as opposed to 5 degrees or more in the periphery. Blakemore (BLAKEMORE, 1970) speculated that " the sharper

decline in stereoacuity with absolute disparity in the centre of the visual field is due to the limits of the amount of bilateral representation in the human cortex" after he had performed stereoacuity on human subjects. This is supported by experiments using a split-brain subject (MITCHELL & BLAKEMORE, 1970) who could not recognize disparities at all in the centre of the visual field although his peripheral stereopsis was intact.

Relative depth discrimination between two objects is finest at the horopter which is therefore the region of maximum stereoacuity. The stereothreshold increases as targets moved along the horopter visual field. This threshold increases exponentially as the targetsmove in absolute disparity away from the horopter (OGLE; 1953, BLAKEMORE; 1970).

The two cerebral hemispheres are not equal in their capacity to analyse stereoscopic material. The right hemisphere which relates to the left visual field appears better at this than the left hemisphere (DURNFORD & KIMURA, 1971). The latter researchers showed this using classical stimuli (vertical rods) and also random dot stereograms in tachiscopic presentation. The special ability of the right hemisphere for analysing visuo-spatial stimuli can be compared to the special speech function that the left hemisphere possesses (KIMURA, 1973).

The stereopsis mechanism demonstrates an after effect (BLAKEMORE & JULESZ, 1971). It has been shown that when a subject adapts to a random dot stereogram consisting of two rectangles of which the upper one is closer to the observer than the lower one and both are equidistant (in opposite directions) in depth from the fixation point, he will, on turning to view a similar stereogram with the fixation point and both rectangles at the same disparity, see the upper rectangle further away than the lower rectangle. The duration of the after effect depends upon the adaptation time.

FIG.2.1 WHEATSTONE'S MIRROR STEREOSCOPE

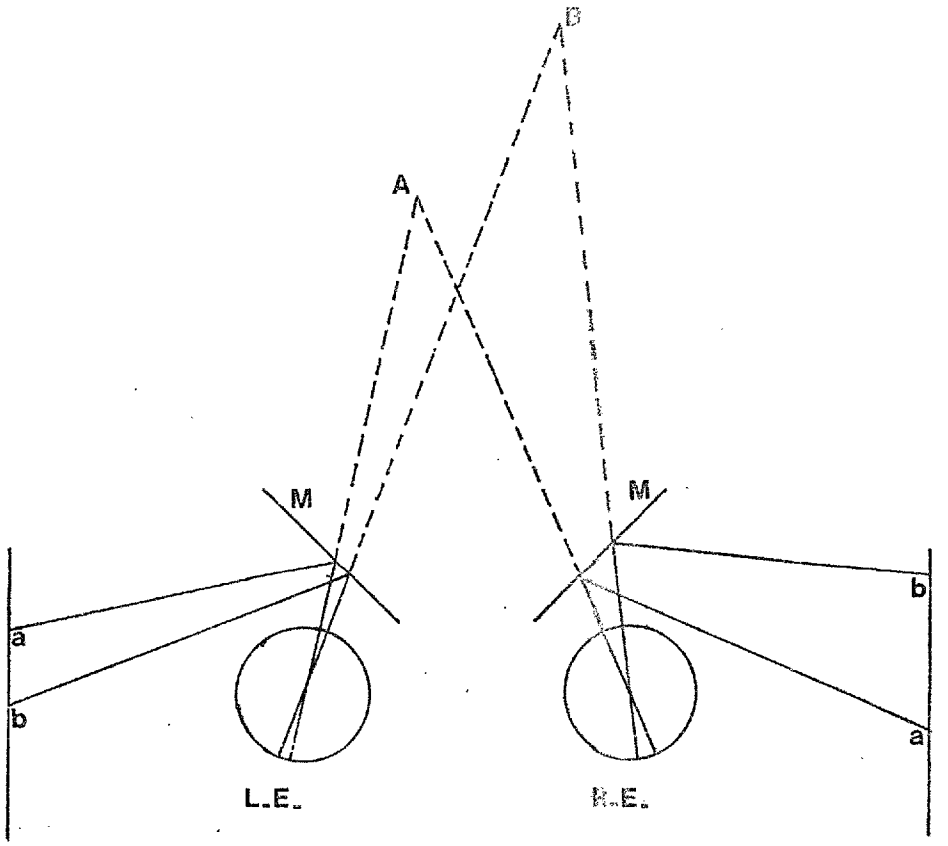
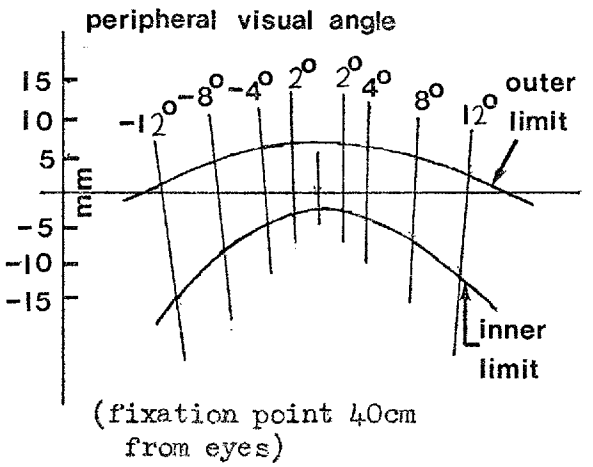
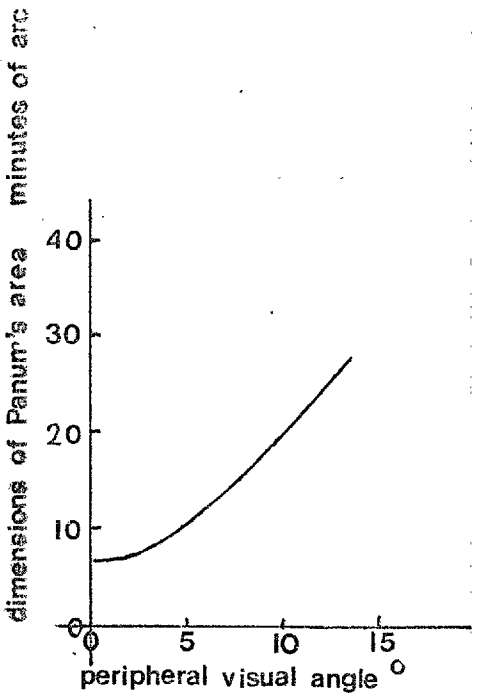


FIG.2.2 EXTENT OF PANUM'S FUSIONAL AREA





Diagrams from data given in "The Eye" (ed by H.DAVSON) Vol. 4 Pt.2 by K.N.OGLE ,London,Academic Press,1962.

FIG. 2.3 HERING'S EXPERIMENT

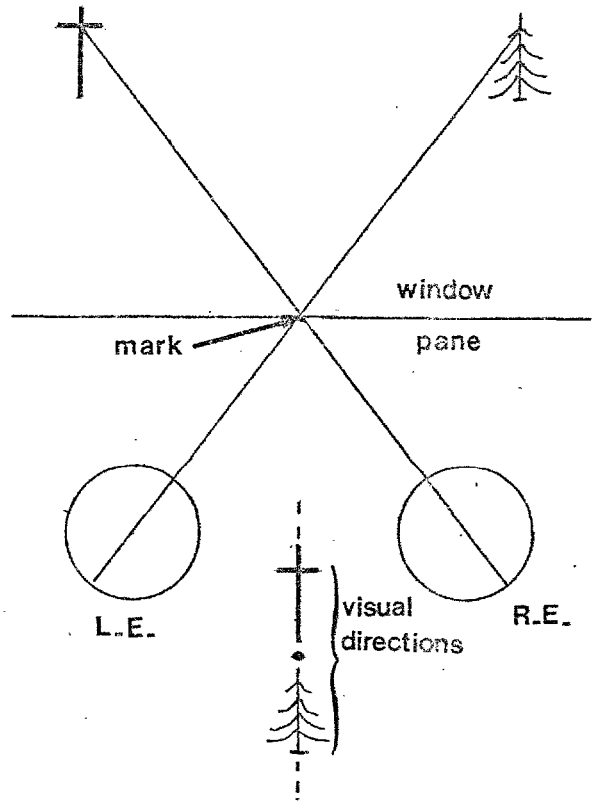


FIG. 2.4 FUSION AND BINOCULAR DISPARITY

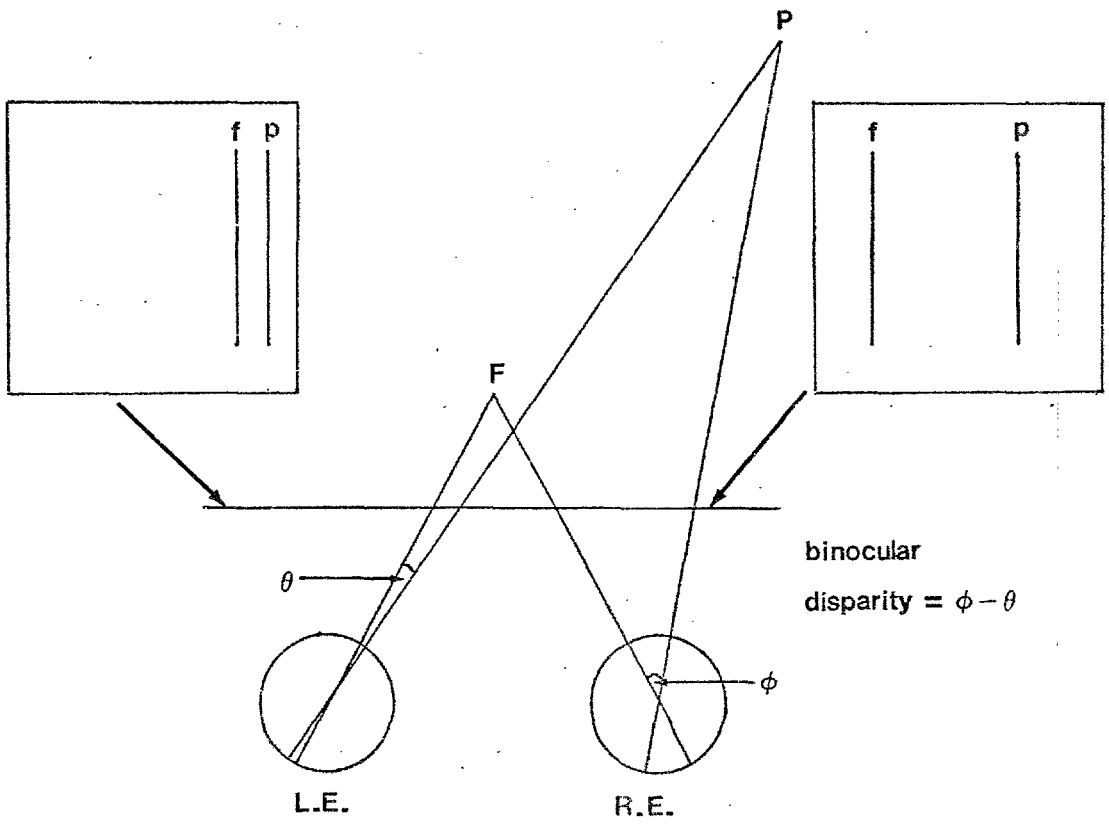


FIG.2.5 Vieth-Müller circle

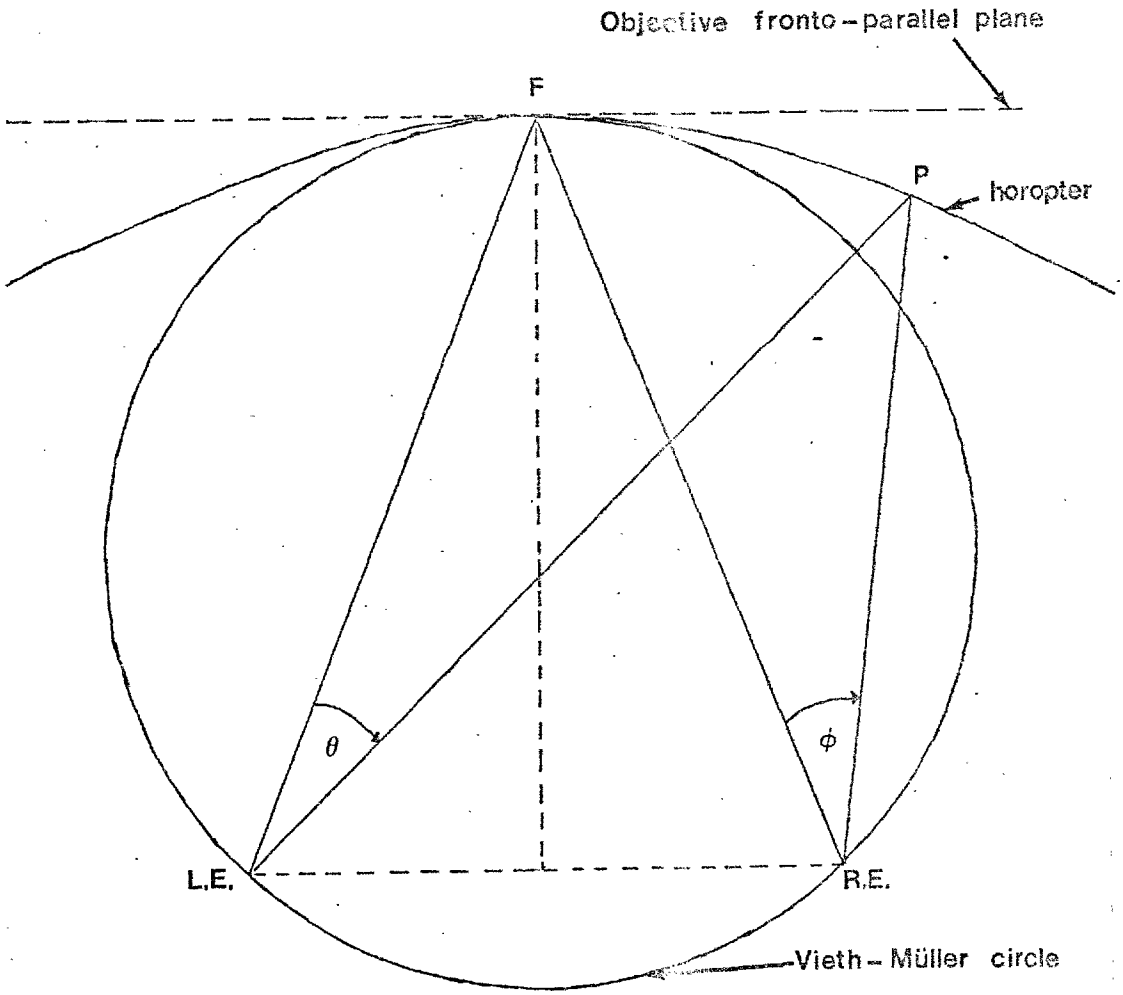


FIG.2.6 STEREOSCOPIC THRESHOLD AGAINST DURATION OF STIMULUS

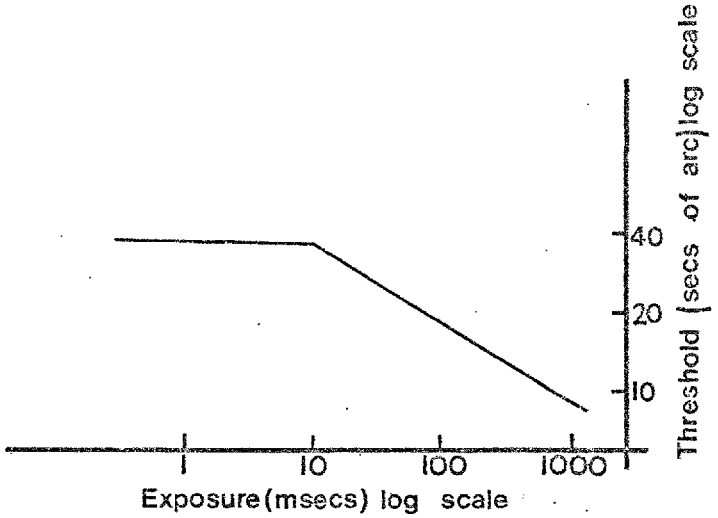
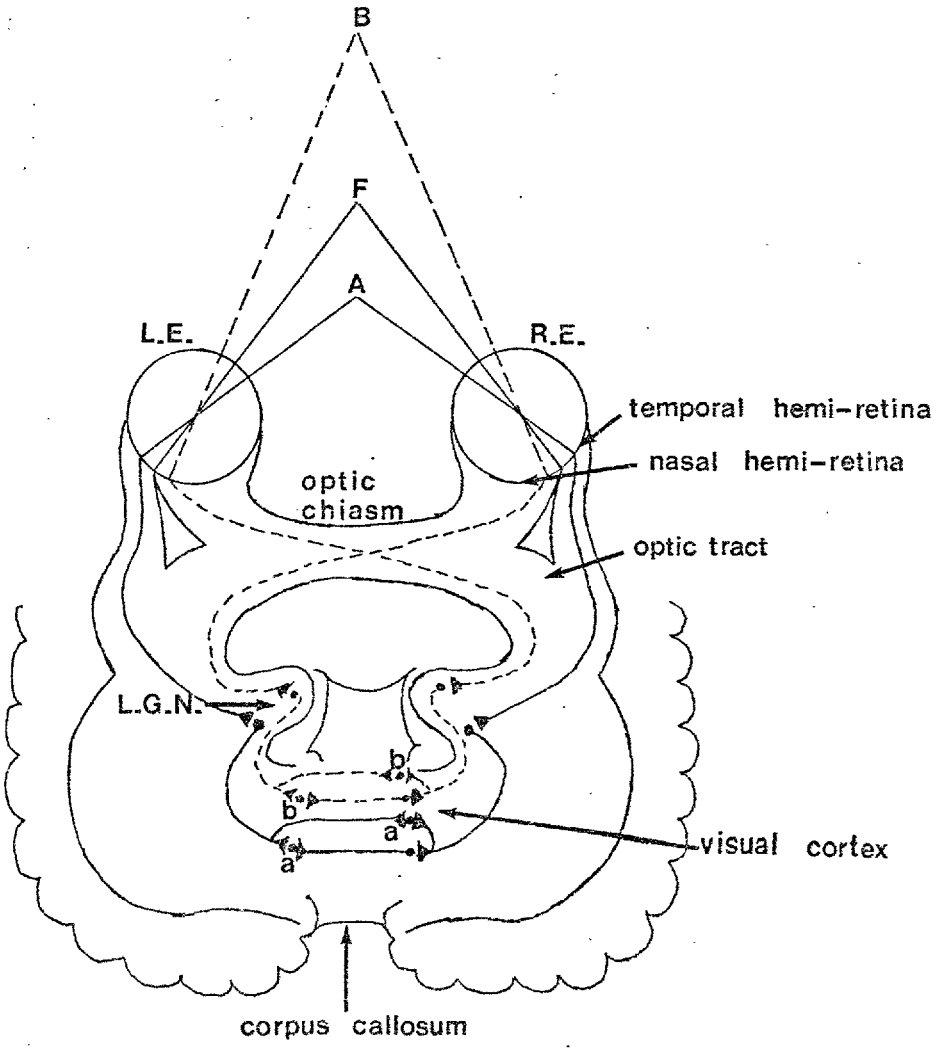


Diagram from data in "The Eye"(ed. by H.DAVSON) Vol.4 Pt.2 by K.N.OGLE London, Academic Press, 1962

FIG.2.7 VISUAL PATHWAYS IN THE BRAIN



CHAPTER 3

RANDOM DOT STEREOGRAMS.

3.1. THE CONSTRUCTION OF A RANDOM DOT STEREO PAIR.

Random dot stereograms or "Julesz" patterns are now widely used for a variety of purposes (see 3.2.) but for the sake of completeness they will be described here. The first computer generated patterns for binocular studies (JULESZ, 1960) were used by Julesz who posed the question of whether binocular fusion preceded pattern recognition or whether monocular pattern recognition was essential before any binocular fusion could take place. He found that it was not necessary for recognisable bodies and shapes to be present in the monocular stimulus for the subject to perceive a three dimensional field in which distinct areas with well-defined boundaries stood out as nearer or further from the subject than some reference plane.

In the real world a human observer uses many cues to determine the relative positions of objects in space (see 2.2.) but in a stereoscope an artificial three dimensional world may be created out of two line drawings which differ only in binocular disparity (DUDLEY, 1951). Figure 3.1a shows a simple stereoscopic situation of three bars arranged in a triangle. In this case, the binocular disparity is convergent (the image of the centre bar in the right field is to the left of the image of the centre bar in the left field) so that the centre bar appears nearer to the observer than the two outer bars. At present each bar consists only of a rectangular boundary for its definition but the stereoscopic situation is not affected if each rectangle is broken up into a grid of two by four . Furthermore, the bars may be given a speckled appearance by randomly filling in the boxes in the grid with

* The triangle exists after stereoscopic combination.

black or white colouring (Fig.3.1b). Naturally the corresponding bar in the complementary field must be speckled in an identical manner or binocular rivalry will result when the two fields are viewed stereoscopically. If, however, the horizontal distances between the bars are arranged to be an integral number of grid dimensions then it will be possible to camouflage the bars by speckling the background in the same way. If the two fields are superimposed then what is left blank is that part of the background which is common to both fields. This area is filled in randomly black or white as before and the same for both fields. Remaining in both fields is a thin strip adjacent to the centre bar which is the background for one field and part of the centre bar for the other (Fig.3.1c). These two areas are speckled independently so that each field is now a homogenous randomly speckled matrix with no vertical bars visible (Fig.3.1d).

The stereoscopic information which exists in the form of binocular disparity for the centre bar has not been altered. When the stereo pair (Fig.3.1d) is viewed stereoscopically a centre bar of dimensions two by four units is seen nearer to the observer than the remainder of the dot pattern. The other two bars that existed in the line drawing stereogram (Fig.3.1a) are no longer distinguishable since there is nothing to distinguish these bodies from the background. Monocularly the entire field is homogenous and in binocular viewing there is no binocular disparity between the dots that lie in these outer bars and those that lie in the background. For the centre bar however binocular disparity brings it out as an complete region in stereoscopic viewing although it is lost in the dot pattern in monocular viewing.

A similar situation exists in aerial photography. Heavily camouflaged installations may not be apparent in ordinary viewing but if a stereo

pair is formed from two photographs taken from different positions the camouflaged object jumps out. Animals of prey normally possess good stereoscopic systems (two eyes at the front of the head) so that their victims, when still, and in a background of similar texture and hue may be detected. A body covered in, for example, leaves and situated in front of a background of leaves presents only one cue additional to binocular disparity for tis detection. This is that leaves on the body nearer to the observer will produce a larger image on the retina than those that are further away. A texture gradient is set up and its is this cue which enables an observer to distinguish between different uniformly illuminated objects which present the same plane image on the retina. The role of texture gradients in slant and depth perception has been studied by Gibson (GIBSON, 1950). In the computer generated patterns of Julesz this cue has been removed and only binocular disparity remains as a cue to depth. It is the omission of the texture gradient monocular cue that makes the random dot stereograms an artificial stimulus. For if a region containing square black and white dots is in front of a similarly textured background then dots in this region will produce a larger retinal image than those dots from the background. Conversely if the dots give the same size of retinal image everywhere, then those which belong to this region must appear smaller than those from the background. This is the size constancy relation embodied in Emmert's law.

In the real world, when the eyes fixate on some distant object near objects will allow one eye to see portions of the background that the other eye does not. Binocular rivalry does not result from the different images that fall on corresponding parts of the two retinae because attention is being paid to the distant object or point of fixation. The observer cannot binocularly fixate on a distant object which lies in only

one field of view. To do this he must move his head sideways so that the near object does not obscure the new fixation point for both eyes. In the random dot stereogram there are regions of dots in one field with no duplicate in the other. In Fig.3.1c these are the thin strips adjacent to the centre bar. Whereas in a normal situation a portion of one field which has no correspondence in the other usually possesses clues which enable it to be attached to an object which is seen binocularly, so that there is no doubt as to whether it should lie in the foreground or background, in a random dot stereogram this is not the case. A particular dot located in one field may be matched with any one of several in the other field giving a whole range of apparent depth. The human visual system however assumes that near neighbours to this dot will lie at or at very nearly the same depth. It looks for a consensus of disparity among the dots clustered together in a particular region. This is how the vertical bar in Fig.3.1d is seen as one plane of dots. The visual system will try to collect the dots which lie in the thin strips on either side of this bar either as part of the bar or the reference plane and will ignore any other solution to the depth location problem. A dot which lies in one of these areas of ambiguous depth (JULESZ, 1960) in one field has a 50 % chance of matching for zero disparity, a 50 % chance of matching for the same disparity as the centre bar, a 25 % chance of matching for both and a 25 % chance of matching for neither with dots in the other field when as in Fig.3.1 a dot may only have one of two possible brightness levels. It is not easy, however, to produce a precise figure from these values of what fraction of the areas of ambiguous depth will become part of the centre bar and what fraction blends into the background since so much depends upon the visual system of the observer. The experiments of Julesz (JULESZ, 1960, 1963), though not directly applicable to this problem, do

indicate the importance of connectivity of point domains in stereopsis. Perturbation to one field of the stereo pair may destroy stereopsis so that only one plane of dots is seen and this is more likely to happen when dots of non-zero disparity are separated by others whose disparity is randomly assigned. However when perturbations are uniformly applied to one field such as by defocusing or by the addition of gaussian or quantising noise stereopsis is remarkably resilent. From this, it is likely that any clusters of dots which, by chance, have the same disparity as the centre bar, (Fig.3.1), will have to be connected to the bar or be of such size that the connection is made perceptually. The quantitative details for this are not known but it is clear from observing stereopsis in a random dot pattern that the boundary between the prescribed region of non zero disparity and the region of zero disparity is ragged. This indicates that parts of the region of ambiguous depth are attaching themselves to the figure, but since this region does not exist as a porous extension of the figure it is clear that connectivity is important. If a succession of independent random dot patterns which themselves yield the same shape at the same depth are presented to the observer in succession at some rate greater than the critical flicker fusion frequency then stereopsis is still maintained but the planes of random dots are now planes of visual noise. The author has found that in this case the boundary between the prescribed region of non-zero disparity and the region of zero disparity is no longer ragged but quite straight. The likely explanation for this is a follows. The ragged edge yielded by each stereogram is different and independent of all others. The stereoscopic visual system is slower than the monocular system so that the observer does not follow the abrupt change from one ragged edge to the next for his stereoscopic system has to look at a binocular pair, each component of which may be made up of

several fields that have been presented in the past. (JULESZ & WHITE,1969). This does not affect the prescribed region of non-zero disparity since the addition of several fields maintains the correspondence between the components of the stereo pair. However, at the edges several fields yielding similar clusters around a given point would be required for these clusters to remain. Another possibility is that the formation of the ragged edge by the observer in a stationary stereogram takes longer than the formation of the main region seen nearer or further than reference plane. If this is so then the ragged edge would be smeared out even more. In practice, with a stereogram of visual noise, perfectly clear boundaries are observed.

According to Julesz (JULESZ, 1971), dots of undetermined depth at a boundary between two planes in a random dot stereogram fall into the plane furthest away from the observer. This means that a figure presented with divergent disparity should appear wider than the same figure with convergent disparity. This effect can certainly be noticed but as has been pointed out earlier a change in apparent size occurs anyway through the operation of Emmert's law although this operates equally in both vertical and horizontal directions. A better illustration of Julesz's rule has been found by the author with the use of a fixation point imprinted into the random dot pattern. This is shown in Plates 4.1 & 4.2 The fixation point is a black cross normally located with zero disparity relative to most of the dot pattern. If a square area is seen in front of this cross the latter cuts out a circle or ellipse out of the square but when the square lies behind the point of fixation the cross stands out quite clear with no dots attached.

3.2. THE USES OF RANDOM DOT STEREOGRAMS.

The most important use of random dot stereograms is as a tool to study stereopsis. Normally the brain is furnished with a range of familiarity cues (see 2.2) with which to aid the location of objects in space. In order to understand the process of stereoscopic vision it is necessary to separate the many cues that may be used by the human visual system. The random dot stereogram removes familiarity cues, brightness gradients and texture gradients and leaves only binocular disparity and for this reason it is the purest form of stereoscopic stimulus that is possible. The results of many classical experiments on stereopsis were open to conflicting interpretation because of the inability to isolate all stereoscopic cues. For examples Doves experiments (DOVE, 1841) on stereopsis under brief exposures were criticised (OGLE, 1962) because the subject knew what to expect but the more recent work on tachistoscopic presentations of random dot stereograms (JULESZ, 1964) demonstrate conclusively that Dove's original statement that stereopsis could take place after exposures as short as one millisecond and that vergence movements were not required was correct. There are many instances where familiarity cues appear stronger than binocular disparity. For example, a face mask presented stereoscopically with each eye seeing what should be the other's field (pseudoscopic presentation (GREGORY, 1970)) should, if the brain's visual system obeyed only binocular disparity, yield a percept of a face with all the depth relationships reversed. However, instead of this "inside-out" face a normal face is seen. In this case it is presumed that the observer's familiarity with the topology of faces backed up brightness gradients and texture gradients prevents the observer from seeing what binocular disparity alone indicates. Despite this and other examples where binocular disparity is overruled the importance of the initial work of

Julesz (JULESZ, 1960) is the discovery that binocular disparity alone is sufficient for stereopsis. Following the neurophysiological evidence (HUBEL & WIESEL, 1968) it is now thought that the disparity cue is fundamental to stereoscopic systems.

When information on disparity is ignored in favour of conflicting information from familiarity cues it is presumably because the subject has a predilection to see what he has learnt to expect even if this conflicts information gained from objective sources. It could be that because of this the human stereoscopic system is not used to its full advantage until an artificial situation is met where familiarity cues are removed. In this respect it is interesting to note that not everybody is capable of extracting stereoscopic information from random dot stereograms. According to Julesz (JULESZ, 1971, p.270) there are a few people who, although not suffering from some inability of one eye or eye co-ordination, strabismus or astigmatism, are stereopsis blind. He found a greater number who had some stereopsis-deficiency in that they have difficulty fusing complex stereograms even though again they apparently suffer from no eye defects. He has speculated that in this case poor stereoscopic performance could have been the result of bad viewing habits. The majority of the population has no difficulty with fusing random dot stereograms according to Julesz and this has been the author's experience. Out of fifty people screened as possible test subjects only three had problems with the basic stereogram and these may have suffered from one of the defects mentioned above.

Apart from the uses of random dot stereograms in the study of binocular vision they may be used in the more general explanation of the human visual system. There are several synaptic junctions between the retina and the visual cortex and in the passage of visual information

along this path the stimulus undergoes some processing. After binocular fusion the stimulus may be further processed so that the higher cognitive processes have an indication of what stimulated the retinae. There are then two stages of processing; firstly the peripheral processing and secondly the central processing (this terminology is not meant to present any analogy between the visual system and a general purpose computer). Random dot stereograms may be used to isolate the function of these geometric processors. A classical stimulus consisting of some geometric shapes may be modified considerably in the peripheral processors to produce some effect. A random dot stereogram may be constructed that, on binocular fusion, yields the same geometric shapes, but since these shapes were not present in the monocular stimulus any special operators in the peripheral processors could have no effect. However any processing done on such geometric shapes in the central processors should be effective and evident. Therefore information in random dot stereograms effectively bypasses special peripheral processing and instead enters at the central processors. This point of entry Julesz calls the cyclopean retina (JULESZ, 1971) after the mythical one-eyed cyclops. An effect evoked by the classical but not cyclopean stimulus would indicate peripheral processing. If the effect is weakly evoked by the cyclopean stimulus then probably both processors are involved. If the effect is produced by both stimuli then this implies that central processing is involved though it is possible that peripheral processing may also be present. If,however, only the cyclopean stimulus evokes the effect then it is probable that the central processing is normally affected by peripheral processing or that for some reason the central processes are not properly stimulated by the classical stimuli.

An example of a phenomenon existing only under classical stimulation is the Hermann-Hering grid (JULESZ, 1965). In this case the inhibitory

effects observed at the grid intersections are presumably caused by the effect of receptive fields with excitatory centres and inhibitory surrounds of the type described by Kuffler (KUFFLER, 1953). Presumably there are no such receptive fields in central processing of the cyclopean retina or depth changes would be expected in a Hermann-Hering grid made by a random dot stereogram.

Most optical illusions are seen when produced in a random dot stereogram. The Ponzo and Muller Lyer illusions may both be observed in this way and in the case of the latter it has been shown that the illusory effect is quantitatively the same for cyclopean as classical stimulation. (PAPERT, 1961).

In the alternate stroboscopic presentation of an object in two different positions perception is divided into three categories according to the laws of Korte (KORTE, 1915). When the duration of the stimuli or the pause between the stimuli is long, the object appears successively in the two sepatate positions. As these durations are reduced the object is seen moving between the two positions. (phi phenomenon). When they are reduced further the object is observed simultaneously in the two positions. It has been claimed (JULESZ & PAYNE, 1968) that in cyclopean stimulation a fourth state exists between optimum movement and simultaneity. In this case a single object is seen at standstill. Julesz and Payne took care to remove monocular movement cues by using two pairs of random dot patterns with the patterns for each pair independent of the other pair. Indeed they found that when the same basic dot pattern was used this fourth state was not elicited. They concluded from this that this fourth state of cyclopean standstill would be masked by monocular movement. However, the author was not able to see this fourth state with stereograms of dynamic noise where no movement cues are available for the changeover of the object from one

position to the next.

Another problem to which random dot stereograms may be applied is the question of pattern recognition and its place in binocular fusion. It is possible to imagine a system where pattern recognition is applied to each monocular field so that lines, squares and circles etc. are extracted and then the two processed pictures fused together. Alternatively a system which first performed binocular fusion and then allowed pattern recognition processes to operate would be feasible. The approach of Julesz (JULESZ, 1960) was as follows. One field of the stereo pair is perturbed before the two fields are presented stereoscopically. If stereopsis results, then the indication is that elementary pattern recognisers are not at work before binocular fusion. This follows from the assumption that the results of pattern recognition would be so different for the two fields that if these results were presented for stereopsis then none could result. It is then concluded that binocular fusion precedes pattern recognition. The difficulty with this argument lies in the understanding of the term "binocular fusion" for fusion must surely involve some sort of pattern matching process in which two fields are used to create one. It is difficult to conceive how patterns may be matched if they are not first recognised to some extent for even in the difference field model of stereopsis (JULESZ, 1960) brightness levels at points on the grid must be recognised for what they are. However, if a particular type of pattern recognition is proposed as a sole process on the monocular stimulus from which the binocular fusion mechanism receives its inputs, and it is then possible to gain stereopsis after one field has been perturbed in such a way that the output from the process might have come from an entirely different stimulus, then it is clear that this pattern recognition process could not have preceded binocular fusion.

Another use of random dot stereograms which may be of importance in future years is the possibility of automatically displaying mathematical functions in three dimensions without any brightness gradients in the display (JULESZ & MILLER, 1962). Random dot stereograms may also be used to screen people for tasks which require good stereoscopic vision.

3.3. FURTHER IMPLICATIONS FOR STEREOPSIS.

There are problems associated with the use of a special type of visual stimulus many of which have been already mentioned. In perception research, the most desirable stimulus is one closest to the real life stiuation. However, if it is desired to evaluate the varous components of the picture and their effect in some proposed neural processing model then it is necessary to create artificial stimuli by isolating these components. It must be borne in mind however, that the stimulus that is simplest to analyse mathematically is not necessarily the simplest perceptually for the subject. When a stimulus that is familiar to the subject is analysed into its elementary(mathematically speaking) parts and each component is applied separately to the subject then, quite apart from any assumptions of linearity in the peripheral receptors, it cannot be assumed that each constituent, being by itself unusual to the subject, will not be processed and perceived by the subject in a quite different way to the complete stimulus which is the sum of these constituent parts. The whole may then be more than the sum of its parts.

A further problem that is common to all experimental research is the inability to prove the null hypothesis. That stereopsis is possible with random dot stereograms is a proof that binocular disparity alone is sufficient but this gives no indication of the extent to which this cue is used when others are present. Another example is the statement

(JULESZ, 1964) that the fact that stereopsis is possible with random dot stereograms displayed to the observer for 1 millisecond disproves Hering's theory on the role of double image. Objects in the visual field whose binocular disparity takes them outside Panum's fusional area are seen double and are crossed or uncrossed depending upon whether the object is in front of or behind the fixation point. Hering stated that objects exposed for too brief a time for vergence movements to possible could still be located in the visual field with respect to some point of fixation by using the double image cue and that this in fact was the principle mechanism of depth location in tachistoscopic illumination. In random dot stereograms no double images are possible since the boundaries of the stereo image are not visible in the monocular stimulus. Stereopsis is possible well outside the classical fusional area of Panum (FENDER & JULESZ 1967). The tachistoscopic experiment with random dot stereograms does not prove that Hering's theory is false but it does indicate that the visual system has the ability to detect depth in brief exposures without recourse to Hering's double image cue. In a real situation this cue may of course be utilised since the disparity information would likely be much less than in stereograms comprising of dots with each component dot yielding binocular disparity.

Tachistoscopic presentation of random dot stereograms with a presentation time of one millisecond is sufficient for stereopsis but because of after-images this gives no indication of the time the visual system requires to take in the information and construct the stereo image. Julesz discovered an elegant method for finding the "perception and attention" time for stereopsis by making use of the properties of ambiguously perceivable surfaces. Wallpaper with repetitive vertical stripes may be seen by an observer in variety of depth planes and this fact is known

as the "Wallpaper" effect. The effect occurs when the vertical stripes subtend a visual angle much smaller than the limit of Panum's fusional area. Then a correspondence exists between the retinae for a disparity equal to the true disparity plus any integral number of periods in the wallpaper pattern. Thus several depth planes are possible.

A random dot stereogram may be constructed, with two possible depth planes in addition to the reference plane. (JULESZ & JOHNSON, 1968) Although most observers are said to have some innate bias (JULESZ, 1971) both planes may be perceived although not simultaneously. However, the ambiguous stereogram is not in the same category of ambiguous stimuli as the Necker cube (GREGORY, 1970). In the latter case concentration on one percept forces the alternation to the other. Perception of one plane in the stereogram is quite stable until the observer makes a conscious mental effort to perceive the alternative. It is therefore possible to present ambiguous stereograms to a subject without the ambiguity being obvious to him.

The procedure for finding the perception time for stereopsis was as follows. First the subject was presented for a time T1 with an ordinary stereogram with a central region lying either in front or behind the reference plane. There is then a delay of time T2 after which an ambiguous stereogram is presented for about eighty milliseconds. The latter may yield a percept identical to the first stimulus or that percept with depth reversed. If T1, the perception time, is long enough and T2, the attention time, is short enough, the perception of the second stimulus is conditioned by the first. The second stimulus effectively erases the after images of the first of which the subject may not in any case be aware of. The two random dot pairs are independent of each other so that no monocular movement cues are present. According to Julesz (JULESZ, 1971) "perception

and attention times are typically under fifty milliseconds".
In this experiment there are two processes at work. The first stimulus provides the information for the stereoscopic system to act upon and if the stimulus is presented for too short a time apparently no action is taken. Information gained stays in the system for a time and will affect the perception of another stimulus provided the time interval between the stimuli is not too great. The stereoscopic system must be thought of as possessing inertia. It requires a certain force to change its state from the quiescent state but in the absence of applied force it takes time to move back to its final steady value.

It may be thought that only the perception time and not the attention time is of importance but this is not the case. In an experiment conducted by the author a subject looked at visual noise binocularly presented by two TV monitors. After a warning buzzer, a stereo stimulus was presented for a few frames in the form of a centre region of dots in front of the reference plane. Because each frame of dots was independent of the next no monocular cues were available for the subject to detect the centre region. Subjects could not detect the brief stereo stimulus when the stereogram giving the centre region in front lasted only one television frame or forty milliseconds. In this case the subject saw only ordinary visual noise with no change after the warning buzzer. However, stimulus was observed when it lasted for two television frames or eighty milliseconds. In this case the stereoscopic system is being fed with continuous information to define the reference plane and it takes time for the system to move out of this state when a different stereoscopic stimulus is presented.

A possible theory for stereopsis with random dot stereograms is that the eyes converge and diverge until correct superposition is obtained for

an area that possesses binocular disparity. This would be equivalent to a serial disparity searching process. The fact that stereopsis is possible in tachistoscopic conditions rules out the use of vergence movements in such a search but it is possible to imagine a neural process equivalent to this taking place. It has been shown that if all the black elements in one field are expanded by 20 % whilst the total area of the dot pattern is kept constant then stereopsis is not prevented (JULESZ, 1963).
It could be supposed that some cortical mechanism exists to allow for this change in the contours as is likely for the case where all elements, black and white, are expanded by 15 % (JULESZ, 1960). This assumption may be premature because a stereoscopic system that was crude and insensitive would not be affected too much by the degradation of an image, the former quality of which it was not able to take complete advantage of. Thus these experiments do not necessarily lend support to the idea of a supreme cortical adapter that does what the eyes cannot or do not have time to do.

3.4. MODELS OF STEREOPSIS.

The first model to be proposed for stereopsis which took into account the results with randm dot stereograms was the difference-field model (JULESZ, 1960). In this model the two fields were superimposed and the brightness values subtracted. Regions of zero binocular disparity would give a zero brightness level whilst other areas (in a random dot stereogram) would give a random texture. The two fields are then realigned with a certain disparity and the process is repeated. If there is a region yielding this binocular disparity then this area is revealed with zero brightness level. The subtraction of brightness levels is no different from a correlation process such as is easy to imagine ocurring in a neural network and therefore seems quite realistic. From the explanation given above a serial

process is indicated but this need not be so. By considering several arrays of binocular disparity specific cells in the visual cortex each array possessing a unique disparity it is possible to conceive of all the operations taken place simultaneously.

The difference field model is an obvious one to explain the ease with which random dot stereograms are fused but it is not so convenient for black and white textureless cartoon images. When texture is present then the difference field model only yields full correlation for a small area which is part of a large figure when the correct disparity is made between the two fields. Without texture that area yields the same value after correlation for a range of disparities. In this case a model for binocular fusion would be simpler if at first monocular pattern recognition were allowed.

The difference field model assumes no distortion in either of the fields. The fact that stereopsis is possible with one field expanded or rotated with respect to the other indicates that further developement of this model is required. But what is more important, no inertia has been put in the system so that there is no description for temporal phenomena or for any hysteretic effects (FENDER & JULESZ, 1967).

There are basically two ways in which hysteresis occurs in binocular vision. Hysteresis in vergence movements was first pointed out by Helmholtz (HELMHOLTZ, 1909). When an object's images in the binocular fields are slowly pulled apart, the eyes diverge to maintain fusion. At a divergence of 8° the fusion is broken and two images are seen. However, if the binocular images are suddenly presented at a separation that requires a divergence angle of a few degrees but less than eight fusion cannot be brought about. The state of vergence in the binocular system thus depends upon the history of vergence movements in the system.

Fender and Julesz, in the paper cited above, suggested that a cortical registration system exists that helps to maintain fusion as images are pulled apart on corresponding retinae and that this system also exhibits hysteresis. Although single vision is always maintained in Panum's fusional areas, eye movements make the cortical system difficult to study. Fender and Julesz used retinal stabilised images to both eyes so that eye movements were eliminated and used a high contrast ratio in their black and white stimuli so that no fragmentation or disappearance or images was experienced. They found that pulling the images apart in stabilised vision with a single vertical line as stimulus gave a break-way point at about sixty minutes of arc disparity and a refusion point at about forty minutes of arc disparity. When a random dot stereogram was used fusion was maintained up to 2^{o} disparity but the refusion point was well back into Panum's fusional area with six minutes of arc disparity. Presumably, the greater binocular disparity information in the dot pattern enabled fusion to be held at a larger separation but the ease of monocular recognition for the line stimulus enabled refusion to occur at earlier as the separation was decreased from the breakway point. It is important to note that the entire dot pattern was moved across the retina and the disparity of the centre region was kept the same relative to the reference plane throughout the experiment. Thus the loss of stereoscopic vision and the separation of the two patterns occurred at the same point of break-away.

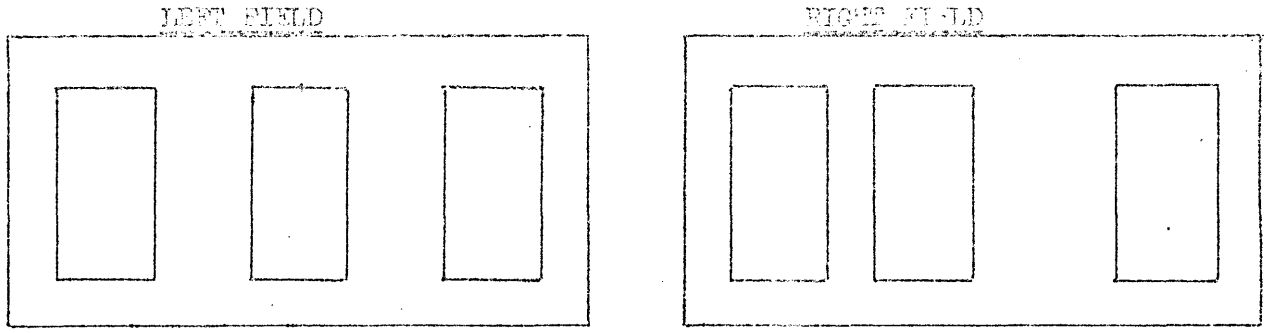
To account for hysteretic effects in the point by point labelling process that is assumed to take place in the visual cortex a new model or analogy of the stereopsis mechanism has been proposed (JULESZ, 1971) and is shown in Fig.3.2. The working of this model is as follows. The magnetic dipoles are ordered in polarity according to the brightness level of the

corresponding point of its retina. The points of the dipoles are connected in the vertical and horizontal directions to each other by springs which restrict the individual movements of the dipoles but not group movements to the same extent. Each retina has a corresponding dipole array. The dipoles are placed side by side by vergence movements and fusion involves the interlocking of these arrays. When the retinae are stimulated by independent dot patterns there is equal attraction and repulsion between the arrays with no resultant force. When there is large identical in both patterns a net attractive force results and the arrays interlock. If the arrays are now subjected to a shear force the ordered group magnetic force opposes this and the interlocking is maintained until the shear strain is too great at which point the attractive force disappears and no net force remains. This is analogous to the point of breakaway. In this model the magnetic force exerted between two groups of dipoles of randomly assigned polarities depends upon the angular displacement of these dipoles about their axis. The system thus exhibits hysteresis, in that after breakaway the two arrays have to be brought back into alignment before a net force exists that will give a uniform angular displacement to these dipoles. If there is a region in the dot pattern that has a relative disparity to the reference plane which is less than the disparity limit after which breakaway occurs., then the two arrays may be subjected to shear strain so that this second region is brought into alignment. Once aligned it remains so even if the shear strain is removed. In this way, an analogy to stereopsis in a random dot stereogram may be obtained.

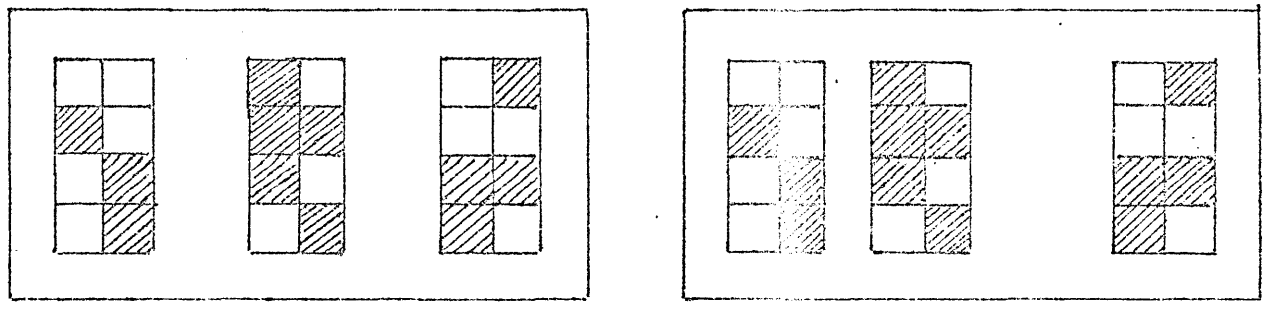
Implicit in the model is the idea of a serial search for binocular disparity. It would seem to suggest that regions demonstrating smaller binocular disparities are found before those demonstrating greater

disparities. Since in this search a force is operating against the attractive force of the already interlocked reference plane more work is required to fuse regions of high disparity. The mechanism of the analogy is tolerant to slight misalignments of the two arrays unlike the difference field model described earlier. The model is also adequate to explain the stability of perceived depth in an ambiguous stereogram since once interlocking is obtained a lot of effect is required to bring about the alternative organisation. However it does not explain the fact (JULESZ, 1971) that in tachistoscopic presentation an ambiguous stereogram is always seen one way for particular subject but that this natural bias may be reversed by a bias in the stereogram of 3 % - 10 % . In the dipole analogy the natural bias would start the search one way and would stop when a sufficient attractive force was exerted. The fact that natural bias can be overruled indicates a parallel search process which cannot be envisaged in the dipole model.

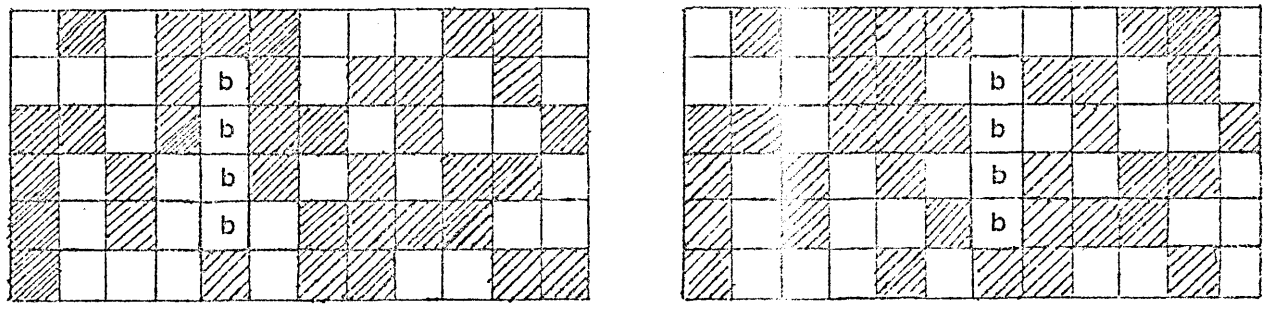
FIG. 3.1 CONSTRUCTION OF A RANDOM DOT STEREOGRAM



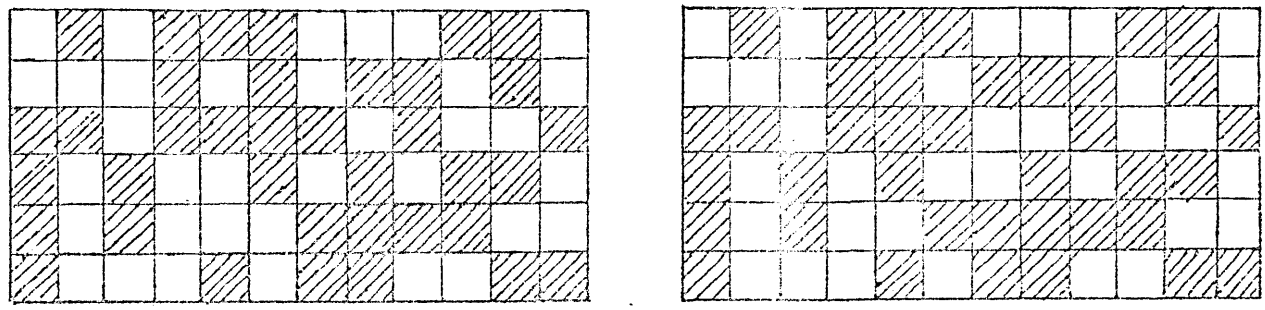
3.1 a Line drawing stereogram.



3.1 b Rectangles given a speckled texture



3.1 c Common background filled in. Ambiguous areas marked b.



3.1 d Complete random dot stereogram.

FIG. 3.2 DIPOLE MODEL OF STEREOPSIS

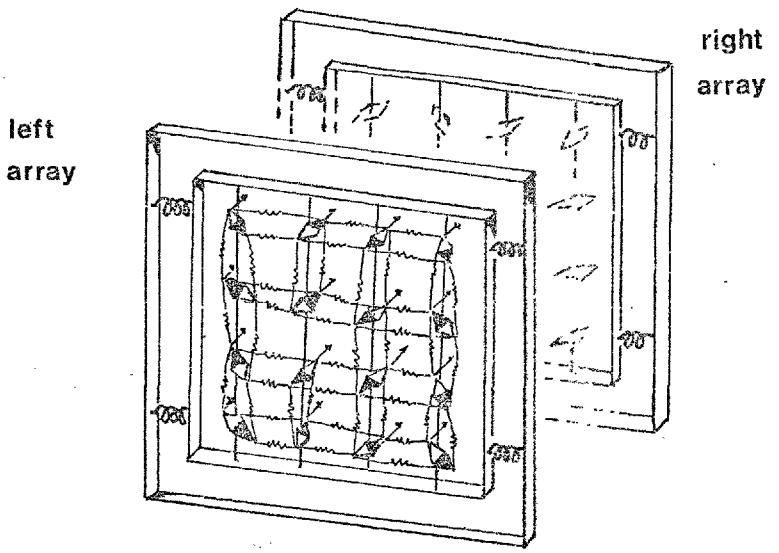


Diagram from "Foundations of Cyclopean Perception" by B.JULESZ, Chicago,Univ. of Chicago Press, 1971.

CHAPTER 4

THE GENERAL FUNCTION OF THE APPARATUS.

4.1. INTRODUCTION

Although it is true that there is an increasing use of special machines, microprocessors, mini-computers etc. in telecommunications, where time sharing of a large general purpose computer becomes either unreliable or uneconomic, this is not generally so in scientific research. The flexibility of the programmable machine makes it more suitable for a developing programme of research whereas a special device may become out of date or unsuitable soon after commission. This argument would hold for research in visual perception except for certain difficulties of computer generated pictures. These are amply described by Julesz (JULESZ 1971, p. 285);- "The problem can be divided into two, depending on whether the researcher wants to use fixed stimulus material or desires to generate the stimuli in real time. While the first stimulus class is within the reach of any university department..... The latter stimulus class is only available for the lucky few..... Unfortunately, visual patterns contain such large amounts of information that even on our present third-generation computers, time sharing is out of the question".

The author's machine is capable of presenting dynamic random dot stereograms with and without interocular delay. The stereo image may be in front of or behind the reference plane of dots and may be of any shape, but only plane images are possible. Complex stereo pictures (JULESZ & MILLER, 1962), which require great storage and mathematical operations for their generation cannot be produced. In the author's apparatus, the size of the dots and the depth of the stereo image may

be varied and it has been found that these and the other variables mentioned are sufficient for the investigations which are the subject of this thesis.

4.2 THE VIEWING SYSTEM.

The viewing system is shown in Figure 4.1. Two television monitors are used. Each screen is covered with a sheet of polaroid with the polarisation orthogonal. The light from the monitors is reflected or transmitted through a half-silvered mirror A. A further half-silvered mirror B enables an illuminated object (such as a fixation point) located in box C to be superimposed on the random dot patterns. Polaroid eye pieces, again orthogonally polarised, enable the light from the monitors to be separated for stereo viewing. The insides and outsides of the wooden boxes containing the mirrors etc. were painted matt black to avoid internal reflections. The polaroid system described here, though very common in stereoscopic systems (particularly in stereo projection systems, where alluminium screens are used to maintain the separate polarisations) suffers from certain disadvantages. The first is that the polaroid plates reduce the overall illumination by 50% and the half-silvered mirrors a further 50 % each. Secondly and of less significance is the fact that oxidation of the anti-reflection coating on the back of the mirrors causes a variation in the spectral response between transmission and reflection. When this becomes noticeable the mirrors must be replaced. Thirdly the polaroids do not give absolutely perfect separation of the two light sources although with the illumination used in the experiments performed such visual "crosstalk" was never observable. The chief advantage of the polaroid system is its simplicity. It requires no elaborate procedures for setting up before each experiment other than a check on the

orthogonality of the polaroid plates. The main alternative to such a system is the use of optical prisms to divert light from two sources separately into the two eyes. These methods do not suffer the same disadvantages as the polaroid systems.

The distance from the subject's eyes to the visual display was 75 cm. The dimensions of the Ampex VM-9A monitor was 14 cm. vertically by 18 cm. horizontally. The random dot pattern did not occupy the entire screen area. If this were done the two monitors would have to be aligned exactly with absolutely identical geometries and the monitor's position in the apparatus would itself be critical. The alignment problem is eased by restricting the Julesz pattern to a rectangular area smaller than the monitor screen. Then the setting up procedure was as follows.
First the gains of each final video amplifier (FIG.5.5) is set to give the equal required illumination at the viewing polaroids. An illumination meter (Holophane Lumeter Tape 48A) was used for this measurement. Then the viewing polaroids were removed so that the observer saw two pictures superimposed. The monitors were moved so that the horizontal disparity was zero (This was essential to ensure that the eyes were converging with the correct angle). The vertical position was then adjusted by the V-hold control so that vertical disparity was zero. Adjustments were then made to the vertical and horizontal size controls to give equal areas in the monitors. The signal going into one of the monitors is then inverted so that in superposition a black dot from one picture added to a white dot from the second picture (the random dot patterns displayed being identical before inversion of one signal) to give a uniform grey. If the picture geometries were not identical, areas of light and dark grey were observed giving a "moonscape" impression. The vertical and horizontal linearity controls were then adjusted to reduce these "bumps" to a minimum. After these adjustments were made, inverted signal was returned to normal

and the illumination was checked. Illumination on a TV screen can of course be varied by the brightness and contrast controls but this is undesirable because of large changes in picture geometry that this causes and it is therefore better to use the video amplifier gain controls. A fine control on illumination is obtained by the sort of amplifier shown in Fig.5.5.

An important characteristic of the monitors when used in visual experiments is the decay time of the phosphors. On the particular Ampex monitors used this was found to be about 1 millisecond by measurement with a phototransistor. This is quite typical for a monochrome television picture tube (RICHARDS 1973, p. 90).

4.3. GENERATION OF RANDOM DOT STEREOGRAMS.

In principle it is a simple matter to generate a Julesz pattern pair on two TV screens or Cathode ray osscilloscopes using ordinary white noise generators. Figure 4.2 demonstrates the scheme. Two random noise generators of identical statistical properties are required together with two tapped delay lines. Noise source 1 would provide the entire picture for one screen which might be presented to the right eye. Then for a line scan system from left to right a vertical bar in depth is seen on binocular fusion if the left eye is shown the picture b which is made up of three separate signals. Picture component A comes from noise source 1. Component B originates from noise source 2 whilst C is a delayed version of noise source 1. A timing pulse T is produced in synchronism with the line scan to indicate the position of the vertical bar and its arrival initiates the insertion of noise source 2 into picture b. The further arrival of T delayed by the same amount as the delayed version of noise source 1 allows the latter signal into picture b until the completion of

this pulse.

The practical difficulty of this arrangement stems from two points. Firstly, the two noise generators must appear to originate from similar statistical processes. The human visual system will easily detect a change in mean or standard deviation of visual noise (JULESZ, 1962). A variation in noise bandwidth causing the size of white and black spots to change their shape and size is also easily detectable. (Bandlimiting causes, for a horizontal scanning system, a lengthening of the dot's horizontal dimension. A further complication can arise with the Benham colour effect. (GREGORY, 1970, p.77). Apparent colour is caused by a low frequency stimulation of the retina causing differential excitation of colour sensitive cells because of their different time constants. This effect, normally demonstrated by Benham's disc is also revealed by a cathode ray tube with a suitable spatial density of randomly stimulated points. If this density varies across the screen then the subjective line which, when produced in this way is very weak, also varies across the picture. There are however no clear demarcation lines in subjective colour perceived even if the density changes abrubtly. This, then, is a secondary effect but could become important in a filtering scheme designed to remove effects of switching transients due to the multiplexing of the various noise sources, by reducing the dot density on the final noise picture.

Switching transients constitute in fact the most serious drawback to be overcome in the system of Fig. 4.2. The human sensory processes are remarkably sensitive to repetitive stimulation. Spikes in an audio signal such as those caused by some switching process are readily detected by a human listener even when the noise level is high so that the periodic signal contains only a fraction of the signal's total power. In a video signal spikes in synchronism with the line frequency, masked with noise,

again are readily detected by the human observer, as shown by Marsh (MARSH, 1967). The human visual system is able to integrate out the effect of additive noise to leave a clear percept of, in the case of the switching scheme proposed in Fig. 4.2., three vertical lines - one for each of the switching points. Marsh did in fact show that horizontal and vertical lines seen in this way can be detected at a lower signal to noise level than lines of other orientations.This is because of the presence of orientation specific line detectors in the visual contex. (HUBEL & WEISEL, 1962).

Finally a problem arises with the delay lines. It is not very important that the pulse T is delayed exactly the same period as noise source 1 but it is important that the delayed noise signal should, apart from its delay be an exact replica of the original. This is within modern technology and for the delays required (a few microseconds) LC delay lines or accoustic delay lines, as used in colour television receivers, could be employed. (HARWOOD, 1970).

All the difficulties listed above are concerned with the problem of removing monocular cues from the stereoscopic stimulus. If the left eye sees vertical white lines locating the boundaries of a vertical bar of dots in front of a reference plane of dots then this, apart from introducing binocular rivalry, gives the observer information about the stereoscopic stimulus which he may use prior to binocular fusion. This nullifies the value of Julesz patterns which were invented for the presentation of pure stereo information without any clues present at the monocular peripheral stages in the visual system.

The author attempted such a scheme with analogue white noise generators but,because of the difficulties mentioned above,abandoned it in favour of a digital method which made use of the properties of pseudo-random noise. This will be described in the next section.

4.4. THE USE OF PSEUDO RANDOM NOISE.

A summary of the mathematical properties of pseudo-random sequences is given in Appendix 1 but it may be noted here that a pseudo-random sequence generator is a finite state machine operating in discrete time in which each successive state is a function of the previous state. When the machine first arrives in a state in which it has previously existed a complete cycle is performed. Thus the output from a pseudo-random sequence generator is periodic but the statistical properties of the signal in one period make it noise-like. In practice, a generator consistes of a shift register store whose cells define the machine state. The feedback function is a linear function, being made up of modulo 2 adders or EXCLUSIVE-OR gates. A maximum length sequence occurs when the shift register goes through all possible states which for an N stage register is $2^N - 1$. The -1 term exists because the all zero state is self perpetuating if all feedback components are modulo-2 adders and is therefore not an allowed state. The generator's output is two level but this may be converted by suitable weighting of outputs at different times to a multilevel noise sequence or, by an analogue filter to continuous wave noise. In the application described here the two level sequence is sufficient. If the sequence length is made long enough compared to the memory of any receiver device then the signal will appear as random noise and its periodic nature is not evident. To generate Julesz patterns the author used a 31 stage shift register to generate a maximum length sequence of $2^{31} - 1$ or just over two thousand million. When the register is clocked at a rate of 5 MHZ then the sequence period is over six minutes. Furthermore, since this period is not an exact multiple of the time for one television frame then the same random dot pattern will not recur even after this length of time.

It is therefore reasonable to suggest that the output of this sequence generator fed into a video monitor will give a picture of two-level random noise.

The chief advantage of using pseudo-random noise for this application is that a stationary random dot picture may be readily obtained. The sequence generator is set in some initial state such as the "all-one" state when each cell of the shift register stores the logic level of unity. At the start of a television frame the shift register is clocked so that it begins to proceed through its determined sequence. At the completion of the frame the shift register is set back into the same initial state and awaits the start of the next frame to go through the same process. When sufficient care is taken over timing a perfect jitter-free stationary random dot picture is obtained as is required to display a binary random dot stereogram of the type that Julesz used. The method of synchronisation control is described in 5.1.

Having produced a pseudo-random sequence it may be processed in the same way as described in 4.2. for analogue signals and shown in Fig. 4.2. There are certain simplifications to this scheme which make the system on the whole more practical. Firstly the problem of obtaining two noise sources of similar statistics is no difficulty but does not in fact arise since use may be made of the "shift and add" property of pseudo-random sequences (Appendix 1.) to generate the same sequence out of phase. Providing this phase difference is made large enough the second sequence will be effectively independent of the first as for as the human observer is concerned yet will possess the same statistical characteristics. This delay line for the analogue noise source now need only be another shift register and the actual delay may be easily varied to set the required binocular disparity and hence the stereoscopic depth. The

switching problems are very much eased now that the system is operating in discrete time and it becomes quite practical to completely eliminate all monocular cues due to switching transients. The second delay line for the timing pulse T might have to be rather a long shift register to cover a complete range of video stimuli but other techniques are used to obviate the need for this.

The digital system can produce stationary and dynamic random dot stereograms readily where all monocular cues may be positively removed. One monocular cue not yet mentioned is caused by each video monitor picking up and displaying a little of the video signal sent to the other or in other words there is "visual crosstalk". Although screened cables carry the video signals to the monitors, screening the monitors themselves would be rather clumsy. The problem of visual cross talk is that when the two components of the Julesz pair are superposed the region A of Fig. 4.2. is reinforces by the crosstalk whereas regions B and C are not. The autocorrelation function of a pseudo-random sequence is such that any non-zero and non-periodic shift gives an autocorrelation of $^{-1}/L$ where L is the sequence length and the autocorrelation at zero and at integral multiples of sequence length is unity. If therefore one component of the Julesz pair is delayed by one bit or one clock period in time then the cross-correlation at zero time shift for the two components a and b (Fig.4.2.) is a uniform $^{-1}/L$ since the extra shift in region B and C gives us less correlation then the single bit shift in region A. The effect of visual crosstalk is then just like an addition of independent noise over the entire picture which does not constitute a monocular cue. This was the system that was adopted in the apparatus used.

A further advantage of pseudo-random sequences over analogue noise sources is the ease with which interocular delay may be implemented.

It is desired to stimulate one retina with its stereoscopic component at a time after the complementary signal has stimulated the other retina. This delay will be of interest when in the range of 1 ms to 100 ms. In principle this can be arranged by adding a delay line in the path of one video source to its monitor. However, since the video bandwidth is about 5 MHZ the number of components for a distortional-free delay produced by an LC delay line would be of the order of 10^6 . This delay implemented with accoustic delay lines would also be unpractical although not so unrealistic (HARWOOD, 1970). With pseudo-random sequences the delay is easily produced by a second but identical sequence generator which is out of phase with the first by a time equal to the required delay. This, of course, has only delayed the picture component of the video signal. For the picture to appear the same, except for its delay, on the monitor the synchronisation information must also be delayed by the same amount. Since the interocular delay required is always much greater than the 64 usecs required for one line scan the best practical solution to this problem is to separate the line synchronism completely from the field synchronism. The line scan is left alone and is identical for each monitor. The frame synchronism is then delayed by an amount equal to the remainder obtained by dividing the interocular delay by the frame period. This delay is easily produced without a long delay line as described in 5.4 . By this method any interocular delay that is an integral multiple of 64 micro-seconds, the time for one line, and is also much less than six minutes, the periodic length of the pseudo-random sequence may be produced. The interocular delays required fortunately fall in this range.

4.5. THE TELEVISION EQUIPMENT.

Figure 4.3. shows the general design for the closed circuit television system. A 10 MHZ crystal oscillator is used to drive the pattern generator as well as synchronising the sync. pulse generator (Philips Type EL 8250/01). Division of the clock frequency by 320 yields 31,250 HZ which for a 625 line 50 HZ system is double the line frequency. This is supplied to the sync. pulse generator which by further division produces its vertical, horizontal, blanking and sync. pulses and so there is never any possiblity of loss of synchronism between the television scanning systems and the digital signal which is developed by the pattern generator. This is essential to ensure a stable stationary random dot picture. Vertical and horizontal sync. pulses are supplied to the pattern generator and mixed sync. pulses are taken direct to the monitors. When interocular delay is required the field component of the mixed sync. is inserted separately into each monitor so that they only run in synchronism as far as the line scan is concerned. Because the crystal oscillator links the pattern generator with the sync. pulse generator it is often necessary to use this frequency or its derivatives to count out timing periods. For example, the time that the sequence generator lies in the initial state before going through its sequence for one frame must be accurately controlled in this way. If this time was dependent upon an RC. network such as a monostable, then the random dot pattern would jerk sideways in a random manner, especially at disturbances to its supply voltage.

A camera control unit (Philips Type LOH 0150) operates a camera in synchronism with the rest of the system. The video signal from the camera may be used to define the shape of the stereo image in the random dot pattern.

When, as described here, the random dot pattern is in step with T.V. sync. waveforms a grid-like picture is obtained with clear vertical lines as well as the horizontal scan lines. This, then, is similar in appearance to the original stereograms produced by Julesz on his computer. (JULESZ, 1960). The black and white dots, however, are not perfectly square but depend upon the frequency which drives the pattern generator. At 5 MHZ which is within the bandwidth of the Ampex VH-9A monitor the horiz./vert. ratio of the dots is about 1.6 which is not too far off square. At 2.5 MHZ the dots look more like hyphons and the depth control which is quantised in dots widths becomes coarser.

In order to compensate for the fact that the observer sees the mirror image of monitor 1 the line scan on this monitor must be reversed so that it scans from right to left. This is easily done by reversing the transformer connections to the horizontal yoke inside the monitor.

4.6. THE STEREOSCOPIC STIMULUS.

The area of random dots in a Julesz pattern that is in front of or behind the reference plane of dots may be defined electronically or alternatively may correspond to any picture picked up by a television camera. The only shapes that can be produced very simply electronically are rectangles which need only four monostables for their definition although they are now integrated in units available for alpha-numeric character generation for television systems. Also television pattern generators have long been available for broadcasting production techniques. However the simplest way to give the stereoscopic stimulus a more complex geometry than a rectangle is to make a black and white drawing and perform edge detection on the video signal emanating from a

camera. This defines the contours of the "in-depth" area and thus all the information required.

Making the internally generated rectangular stimulus move is an easy matter requiring pulse width modulation of the distance from the left hand edge of the screen to the start of the rectangle. This is described fully in 5.1 . Alternatively effecting a mechanical movement of the camera's subject will do the same thing although this is more difficult to arrange for precise trajectories.

If in Fig. 4.2. the left eye sees picture b and the right eye sees picture a then the vertical bar defined by area C will appear in front of the main common area A. If each eye is presented with the other eye's view then C should appear behind A for now the binocular disparity is divergent. The extent of this disparity produces the amount of apparent depth of the stereoscopic stimulus and is varied by a switch which selects the required tap on the shift register delay and also the width of area B. Reversal of depth may be implemented by interchanging the polaroids in the eye pieces but it is better for experimental purposes to be able to change the depth plane without the subject's knowledge. Switching pictures a and b (of Fig. 4.2.) between the monitors is the simplest way to do this. Providing the subject does not have eidetic memory he will have no monocular cues available to him for ascertaining whether the stereoscopic stimulus is in front of or behind the reference plane of dots, pictures a and b appearing the same to each eye before binocular combination When interocular delay is being used interchanging the monocular stimuli is a little more complicated since the two components differ also by a time delay as well as binocular disparity.

In most of the experiments conducted by the author stereoscopic

stimuli were presented for a short time to subjects. There are many problems with such tachistoscopic presentation caused by the nature of television. With interlaced scanning, as was used here, a complete television picture consists of two fields each requiring 20 milliseconds for their complete description. Visual stimuli derived from televisions cannot then be presented to a subject for less than one complete frame or 40 milliseconds and at least for presentation times not far different from single frame all display times must be quantised in 40 milliseconds steps. If this is not done some parts of the picture will be seen more than others. In any case the disadvantage of seeing the top part of the picture before the bottom half is always present unless an attempt is made to randomise the starting position on the screen. However in experiments on facial recognition Garneau (GARNEAU, 1973) attempted to discover the important features of a human face that enable it to be recognized. He used exposure times of two or three frames and was therefore in a situation where results indicating the greater importance of, for example, the forehead over the chin could be affected by the fact that the forehead was always seen first. Yet, on repeating his experiment with the television monitor turned on tis side, so that he had a vertically scanning system, he found no significant difference in his results.

In experiments on binocular vision it is important that when visual stimuli are presented in brief exposures there is no time for vergence movements to take place. It has been shown (RASHBASS & WESTHEIMER, 1961), in their investigations on the dynamic behaviour of the vergence movements performed by the eyes, that a delay of approximately 160 milliseconds occurs before the eyes react to a stereoscopic stimulus in order to change their point of fixation. This means that in a stereoscopic exposure of

80 milliseconds or two television frames the experimenter may be confident that the eyes cannot move to fixate on the "in-depth" region of dots. If these eye movements were much quicker, so that the binocular system could react before the television frame had been completed, then a television system such as the one described here could not be used. For exposure times of less than 40 milliseconds conventional tachistoscopic methods must be used.

With the equipment described, there are available several methods of presenting brief stereoscopic stimuli. Firstly it is possible to flash up a few frames of the video signal from a blank picture as in a normal single field tachistoscope. If, with the video switched off, the monitor's screen is completely black, then the sudden application of the signal causes a small drop in the high tension voltage which causes in turn a brighter area at the top of the screen until this voltage falls to a steady value. Therefore, strictly speaking, the monitor should not be used in this way unless a large high voltage capacitor steadies the high tension line. Problems may also arise if there is a d.c. component in the video signal and a large input capacitor together with a high input impedance in the video amplifier. This will cause the picture to become brighter at the bottom. This method is then not very desirable for a television system and suffers some disadvantages because of the change in illumination between the blank screen and the visual stimulus. The eye requires time to accomodate to a change in illumination and for this reason a system similar to the one described by Julesz (JULESZ, 1964) is to be performed. In this method both eyes focus on identical random dot patterns with, therefore, no special "in-depth" area. The stereoscopic stimulus is presented by removing these patterns and replacing them for

a short time with another pair of patterns independent of the first and which contain binocular disparity over some region. The overall illumination does not change in this changeover and no monocular cues are present either.

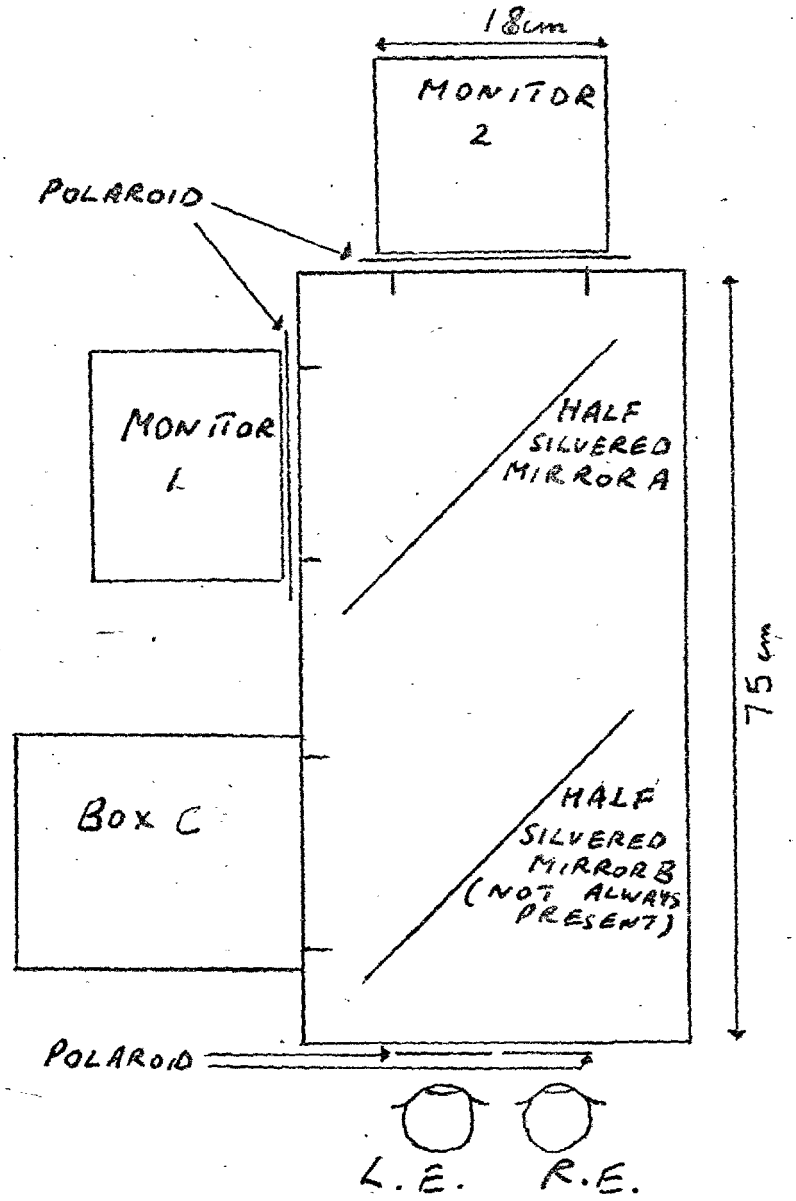
A system, based on this method, may be readily implemented on the apparatus. A stationary random dot picture is presented to the subject which is then changed to another by putting the pseudo-random sequence generator into a different initial state at the start of each frame. The new initial state is, of course, far removed in phase from the original initial state so that the two successive pictures are effectively independent. The "in depth" area exists only for the time that the second random dot pattern is presented. In Fig. 4.2. this means that initially both eyes see picture a; secondly a new random dot picture is produced and one eye now sees picture b; finally the initial situation is repeated. Without the new random dot pattern a monocular cue exists for the eye that sees the change from a to b. Again using Fig. 4.2. what one eye sees is an apparent movement of the dots contained in area C from left to right. This defines the boundaries of the "in depth" area of the pattern and therefore constitutes a monocular cue. The apparent movement observed is an example of the phi phenomenon as applied to random dot patterns which has itself been a subject of studies (ANSTIS, 1970).

An alternative method for presenting a stereo stimulus without any monocular cues or changes in illumination at the instant of exposure is to provide the subject with two identical dynamic noise patterns and then to change one to yield an "in-depth" area. Since, in dynamic noise, each television frame is independent of its predecessor no monocular cue arises in the changeover from picture a to picture b (Fig.4.2). This method may

also be used for presenting random dot stereograms with interocular delay but if it is desired that no interocular delay should be present before the actual stimulus is presented another method is possible. Both eyes are presented with identical stationary random dot pictures. Then one picture changes from stationary to dynamic noise. At a later time the other picture does the same. These dynamic pictures last for the same total length of time after which the situation returns to two identical stationary pictures. When the pictures consist of dynamic noise the two form a Julesz pair with of course, interocular delay. In this way, there is no change of illumination and no indication of interocular delay before the stereo stimulus is presented.

4.7. THE FIXATION POINT.

As mentioned previously it is desirable to provide a point for the subject to fixate upon so that the position of some brief stimulus on the retina may be defined. In Fig. 4.1. an illuminated spot inserted in box C will provide a fixation point but if there is a continuous random dot display the spot will have to be more intensely illuminated and possibly of a different hue for it to be seen readily. This is undesirable and furthermore the position of the illuminated spot will have to be precisely located in box C so that the fixation point lies in the plane of the random dot pattern or at an exact distance in front of or behind the pattern as required. A better method is to insert the fixation point as a small cross made up of black or white dots in the random dot pattern. The dimensions of the cross are then quantised in dot sizes and binocular disparity may be added again in steps of a dot width. Plates 4.1 and 4.2 show examples of random dot patterns formed as described here with the fixation point inserted.



NOT DRAWN TO SCALE

FIG 4.1 LAYOUT OF APPARATUS

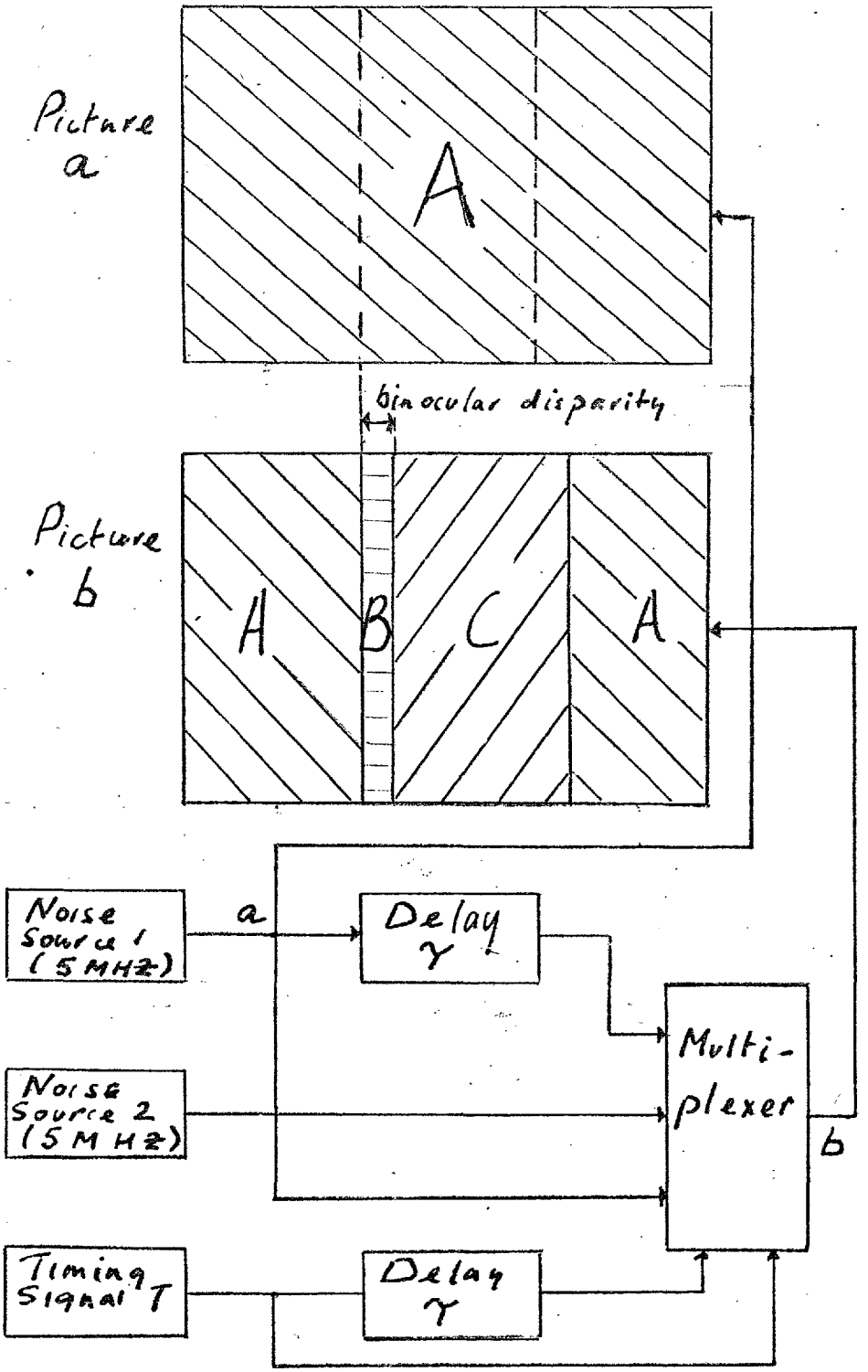


Fig 4.2 Generation of Julesz pair with random noise generators

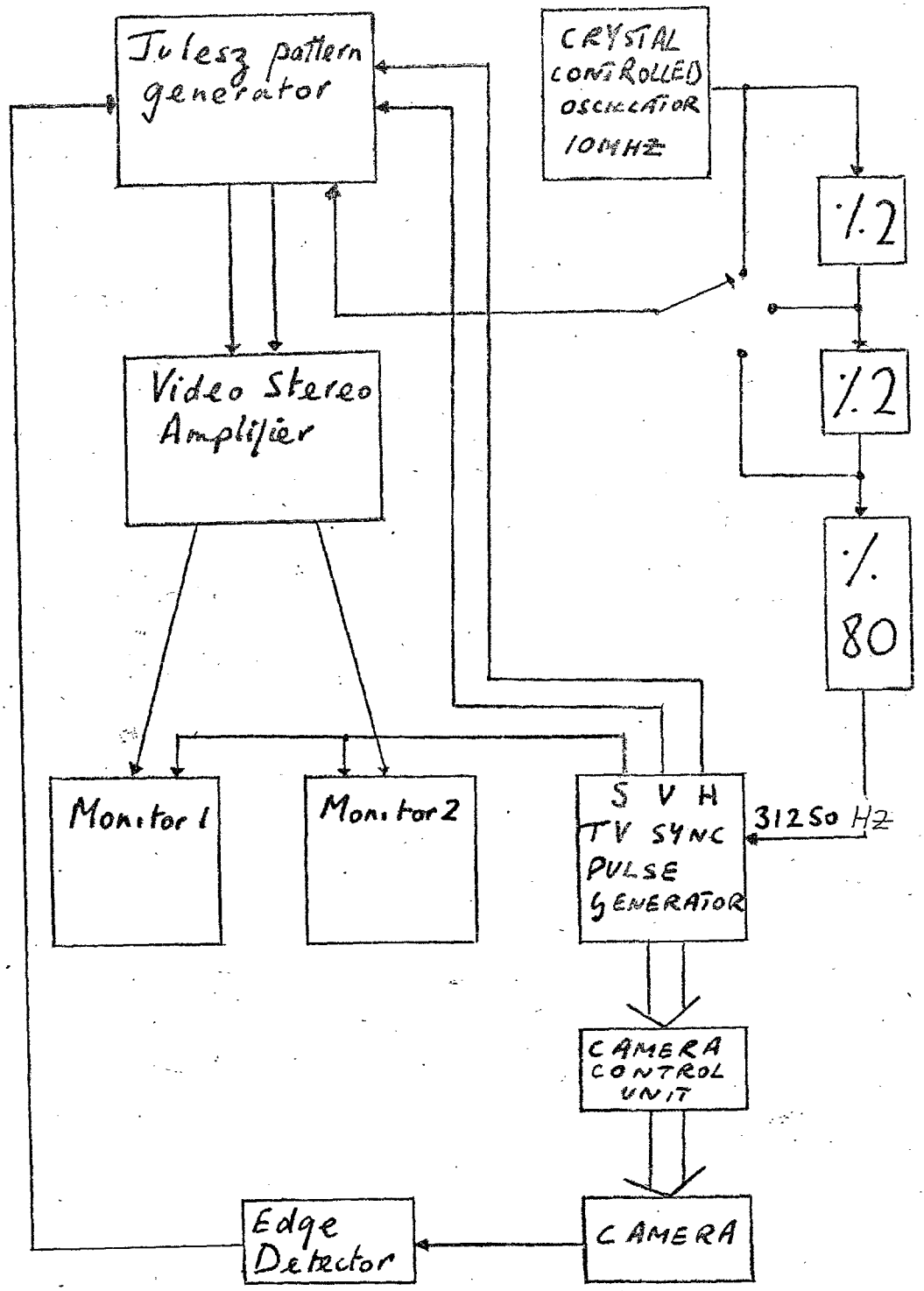
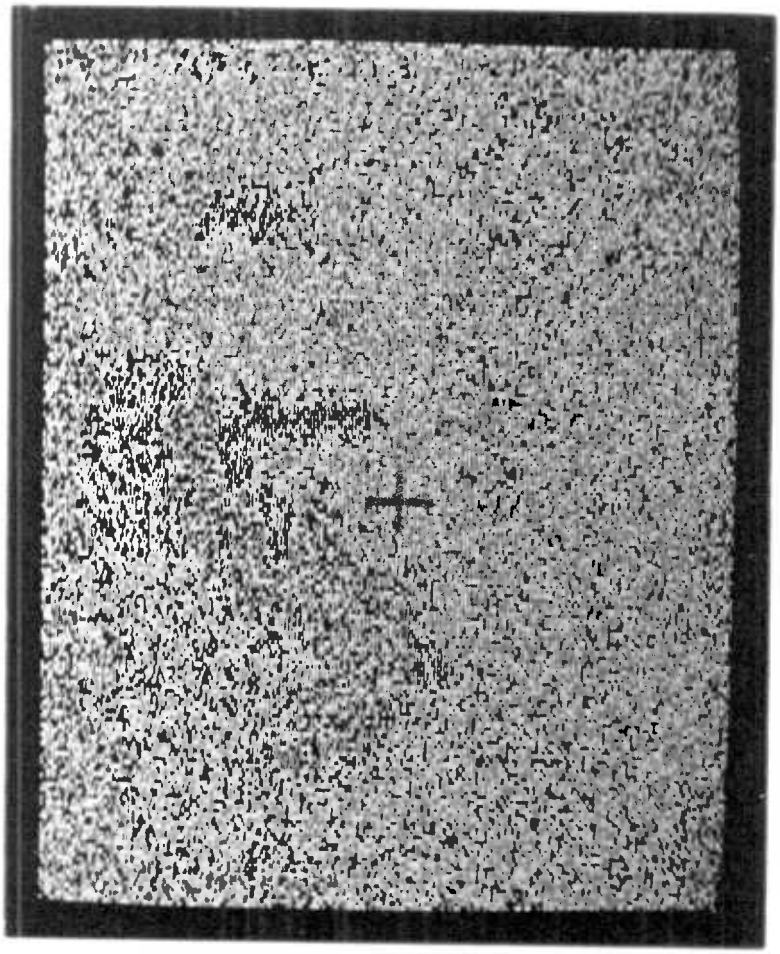


Fig 4.3 Layout of television equipment.

A NOTE ON VIEWING STEREOGRAMS

The stereograms displayed in Plates 4.1-4.10 may be viewed by holding the stereo pair about 40 cm from the eyes which should fixate on a much nearer point. The centre of the left image may then have the same visual direction in the right eye as the centre of the right image in the left eye. With a little practice these stereograms may be fused readily.

PLATE 4.I SQUARE BEHIND (DISPARITY 3 BITS AT 5 MHZ)



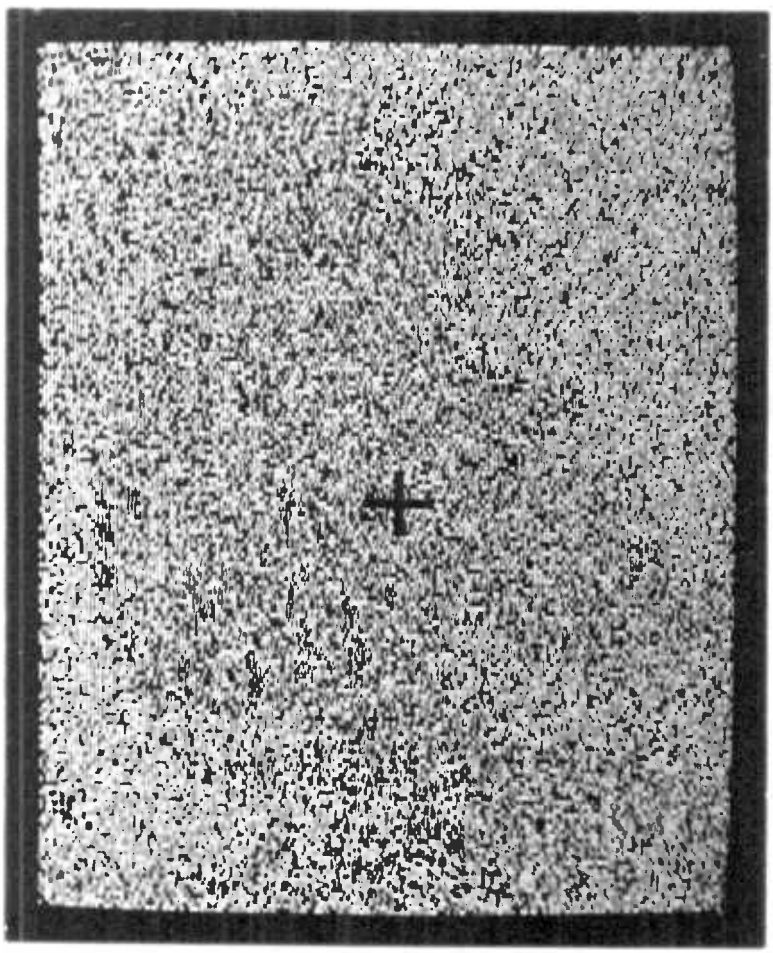
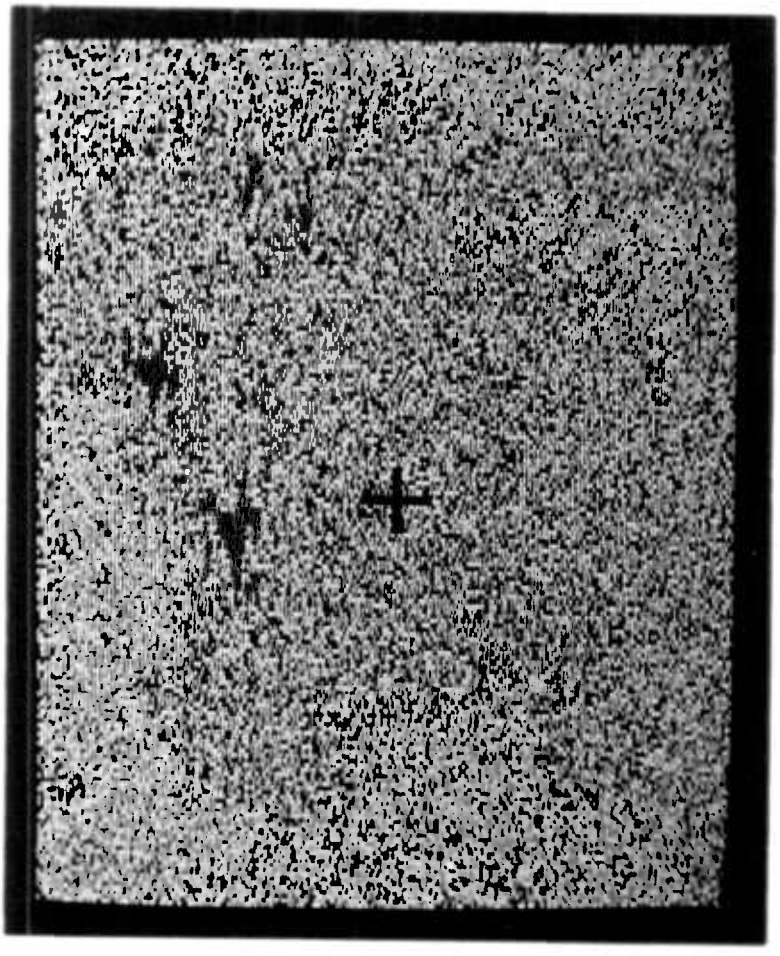


PLATE 4.2 SQUARE IN FRONT (DISPARITY 3 BITS AT 5 MHZ)



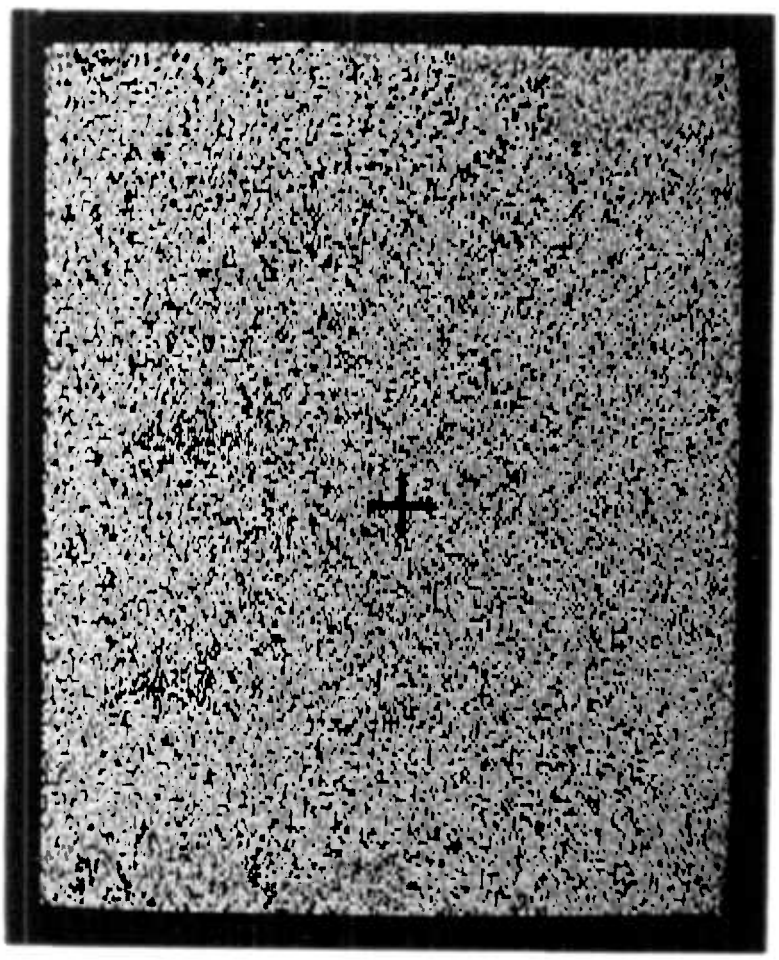
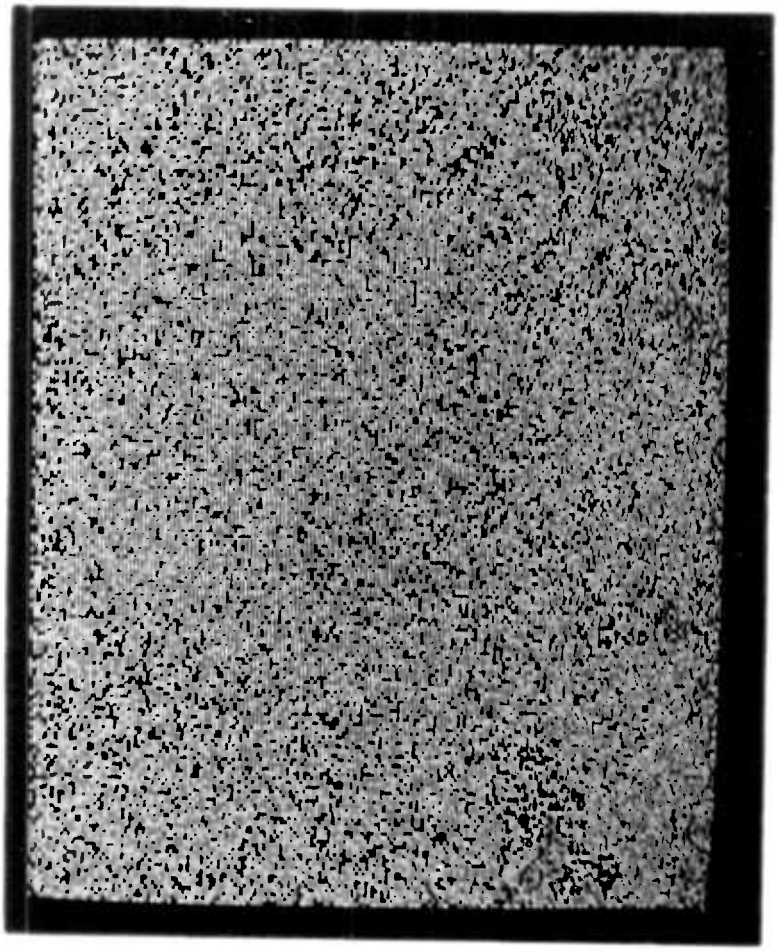
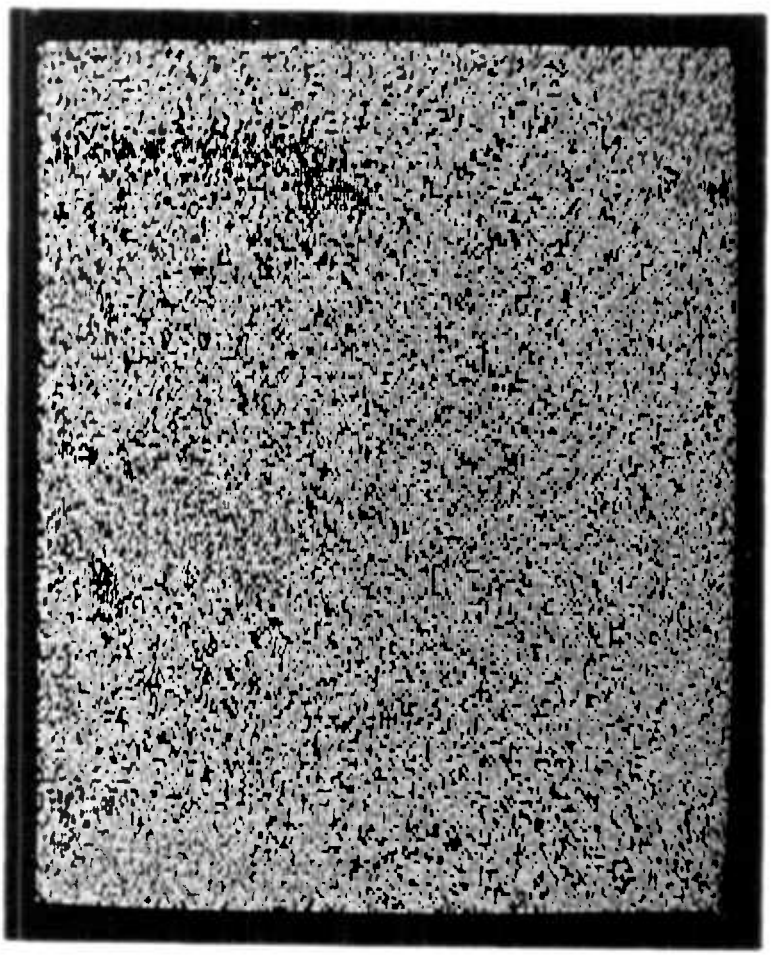
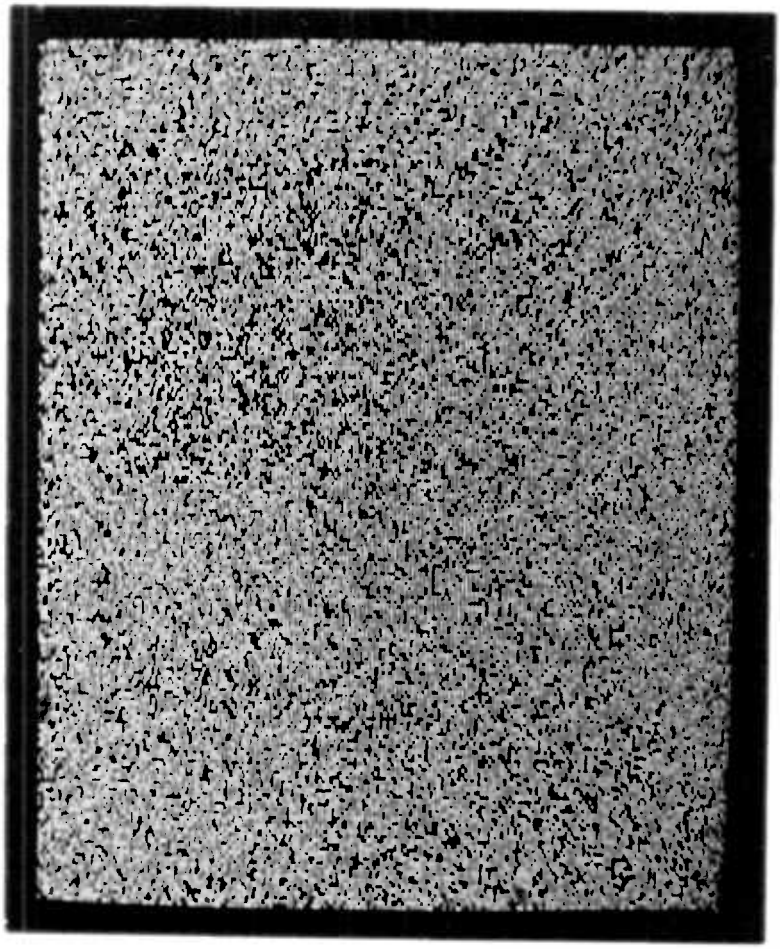


PLATE 4.3 SQUARE BEHIND (DISPARITY 6 BITS AT 5 MHZ)







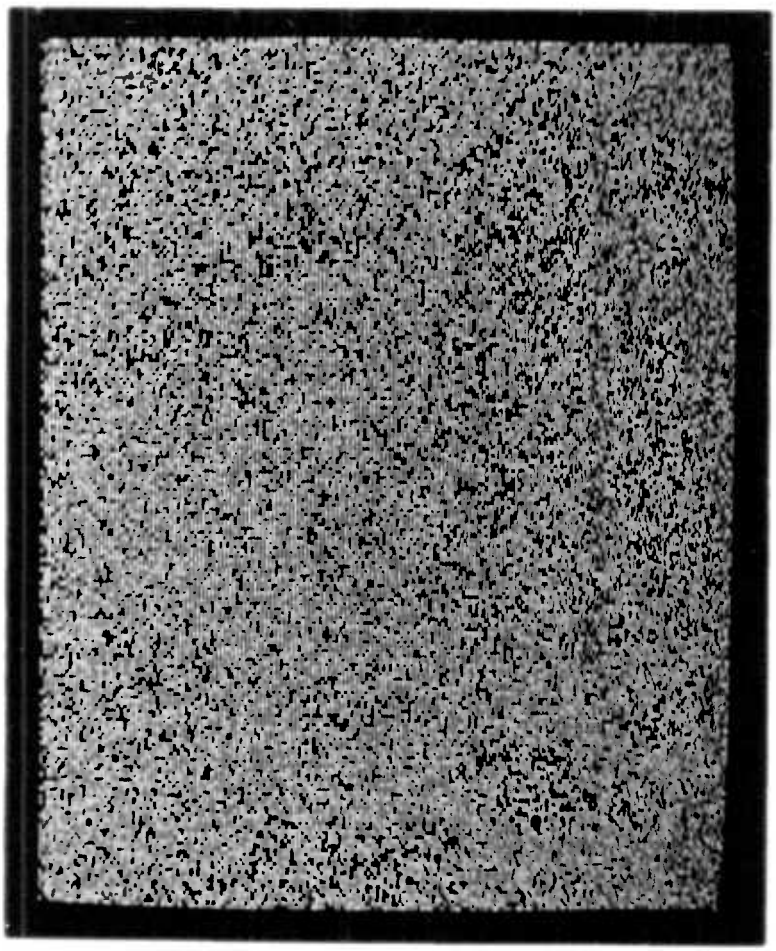
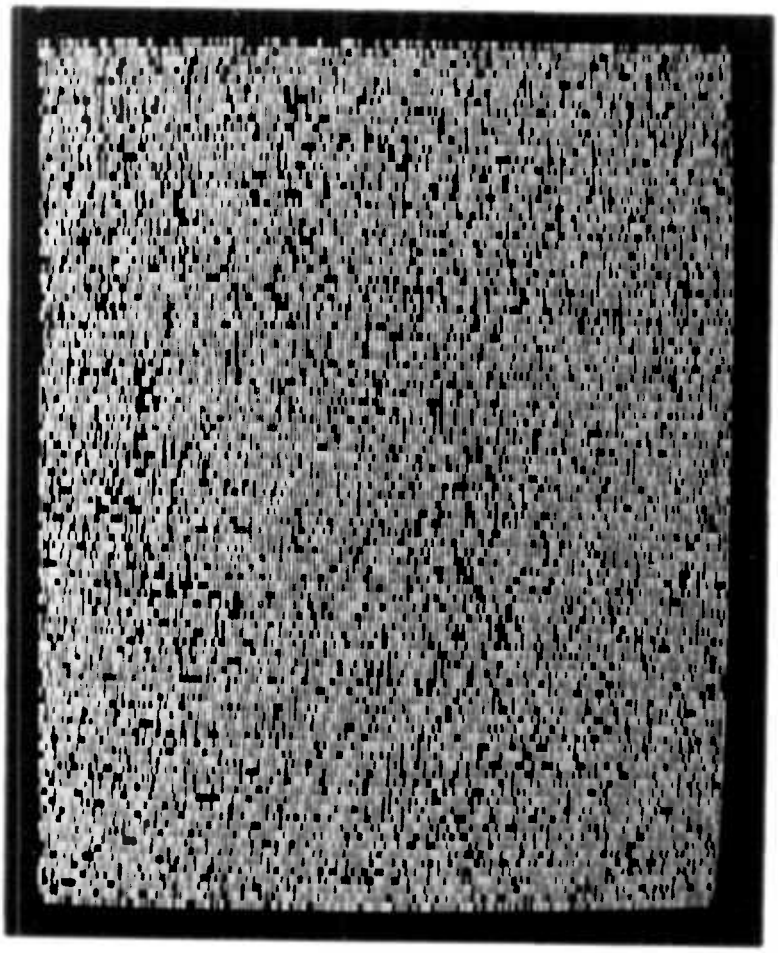


PLATE 4.5 SQUARE BEHIND (DISPARITY 3 BITS AT 2.5 MHZ)



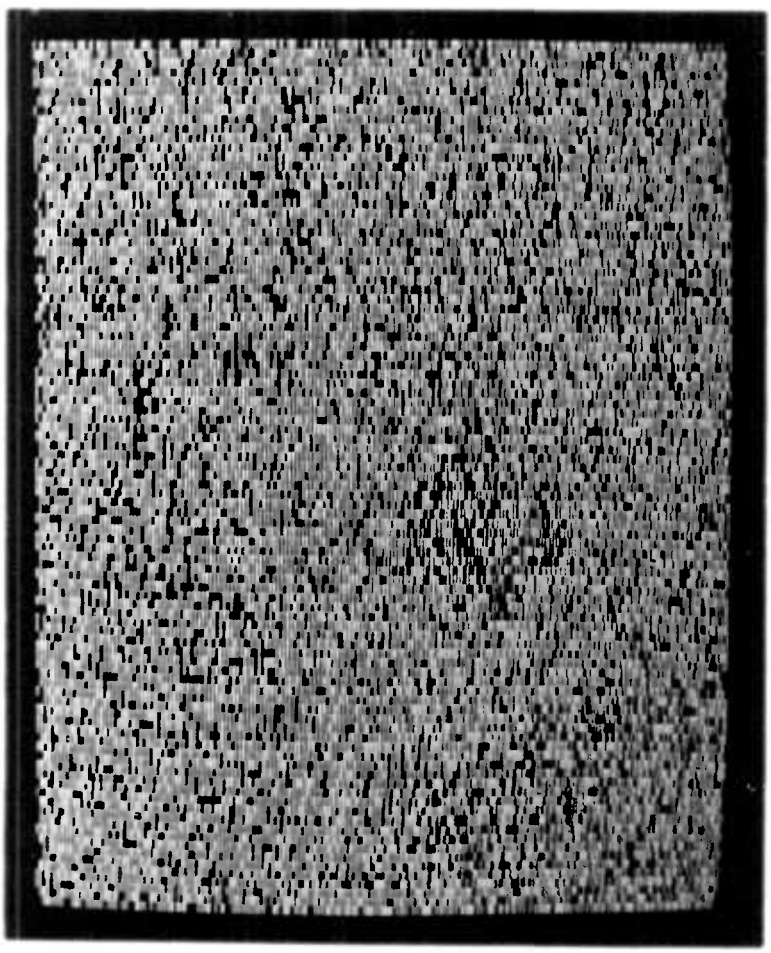
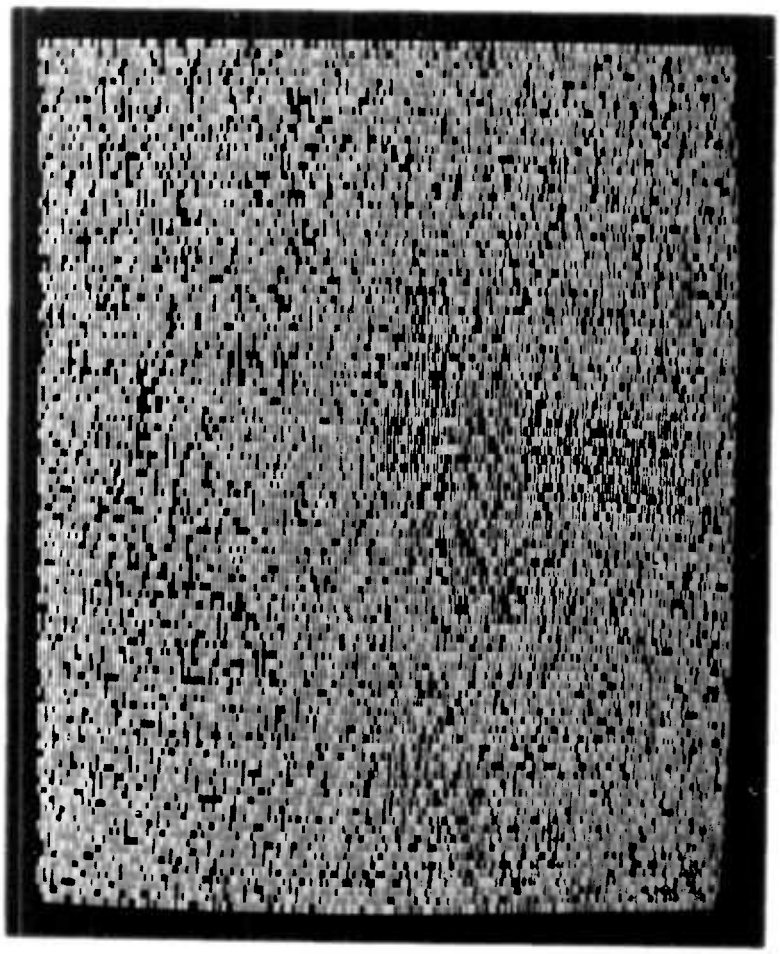
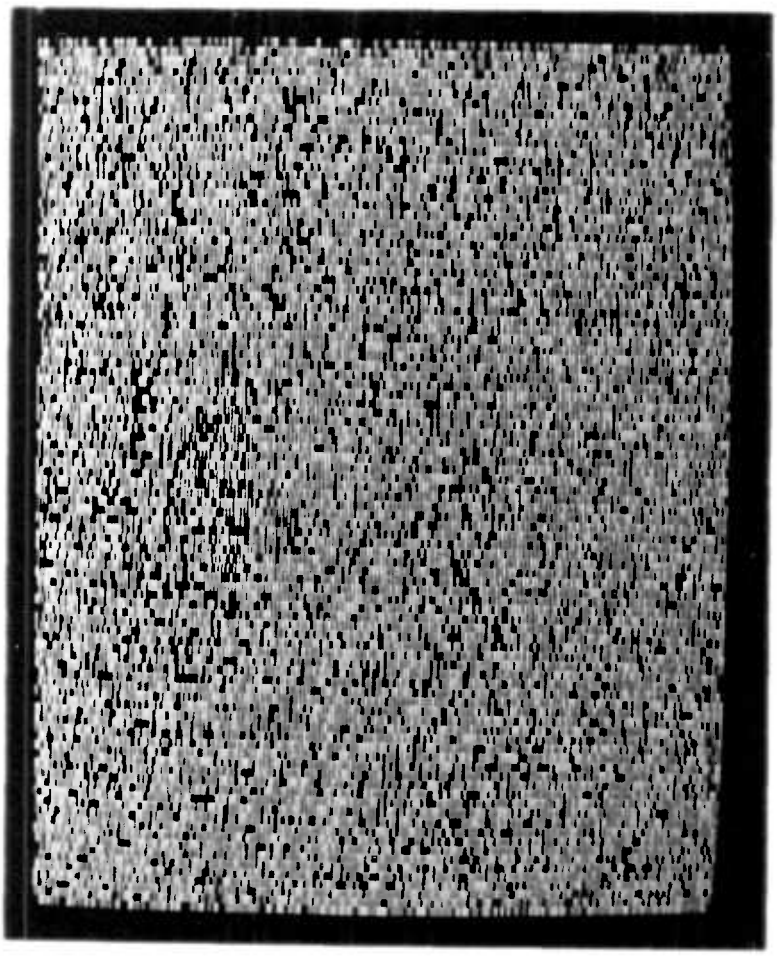
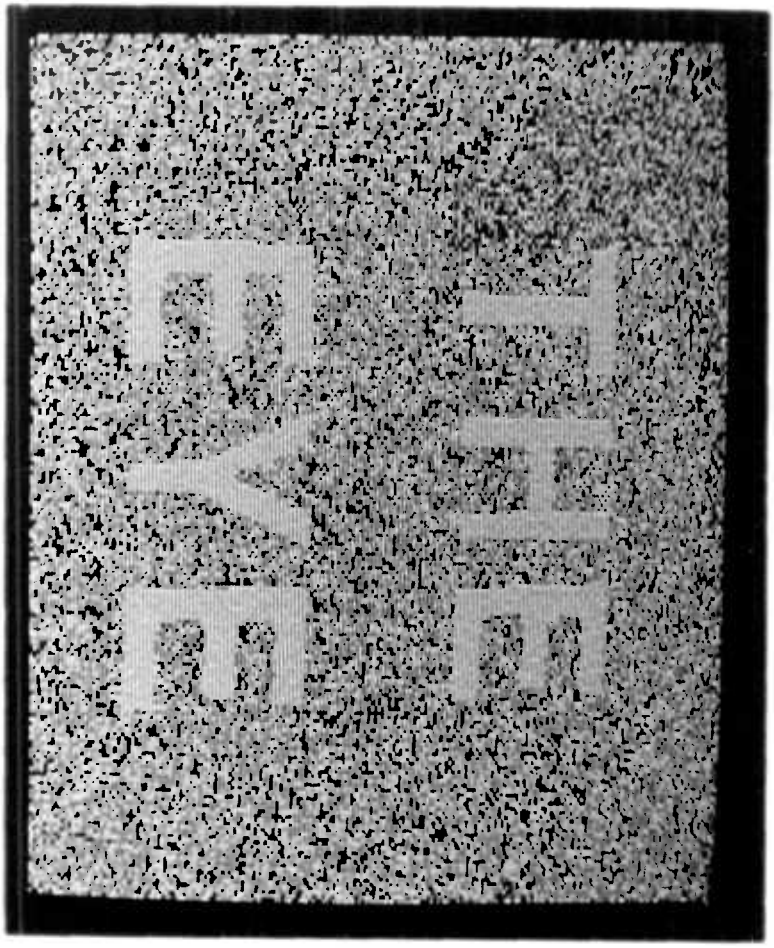


PLATE 4.6 SQUARE IN FRONT (DISPARITY 3 BITS AT 2.5 MHZ)







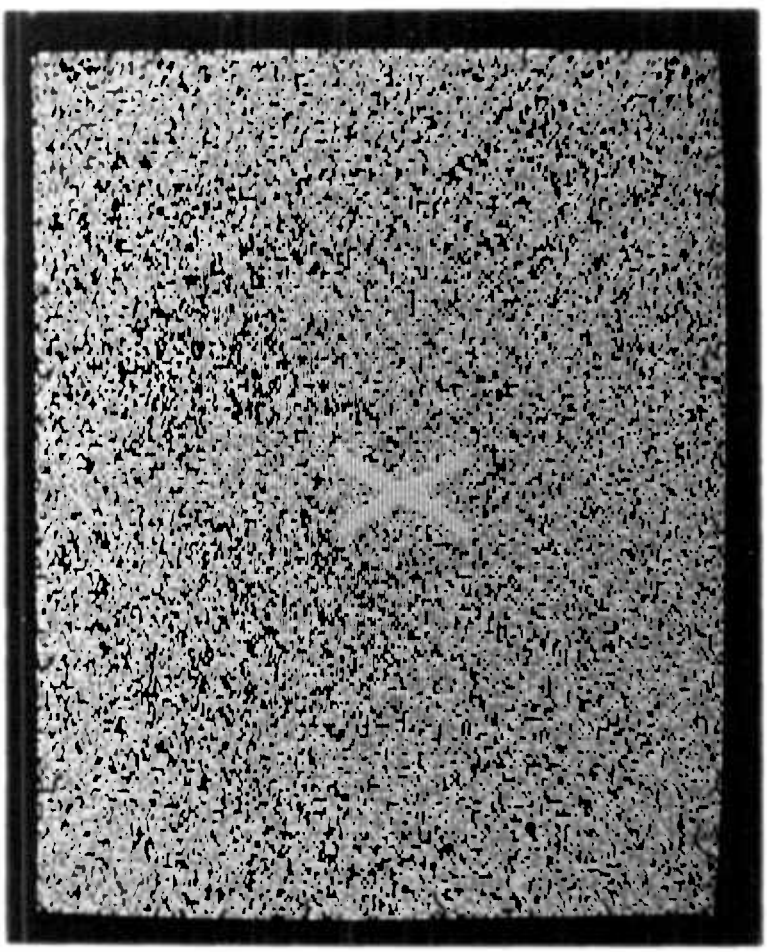
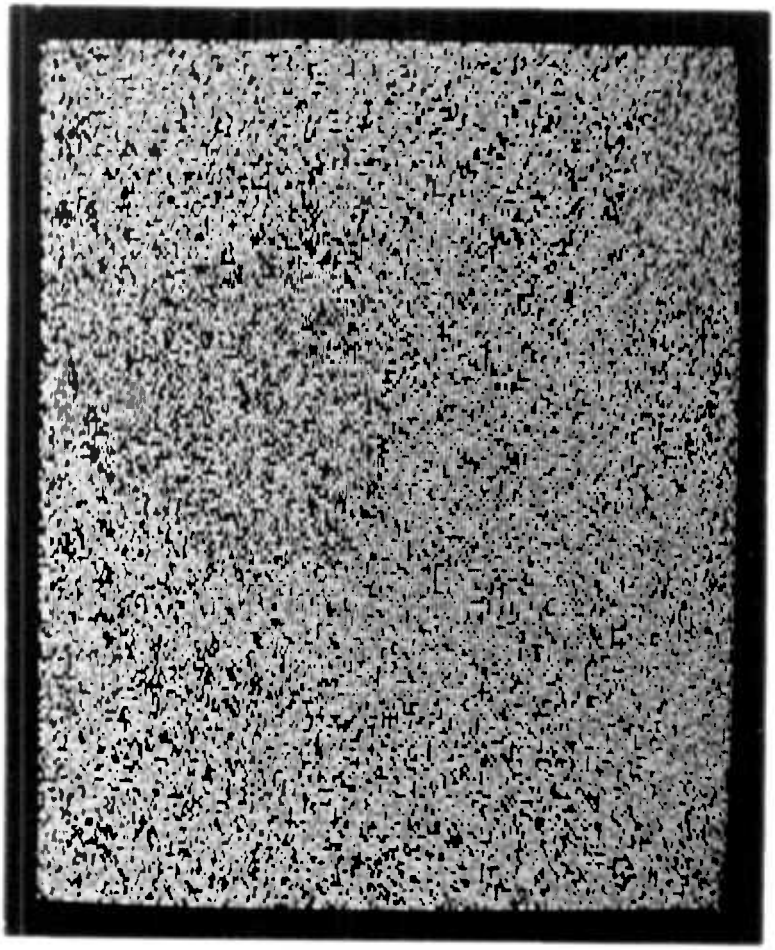


PLATE 4.8 "THE EYE" IN FRONT(DISPARITY 3 BITS AT 5 MHZ)



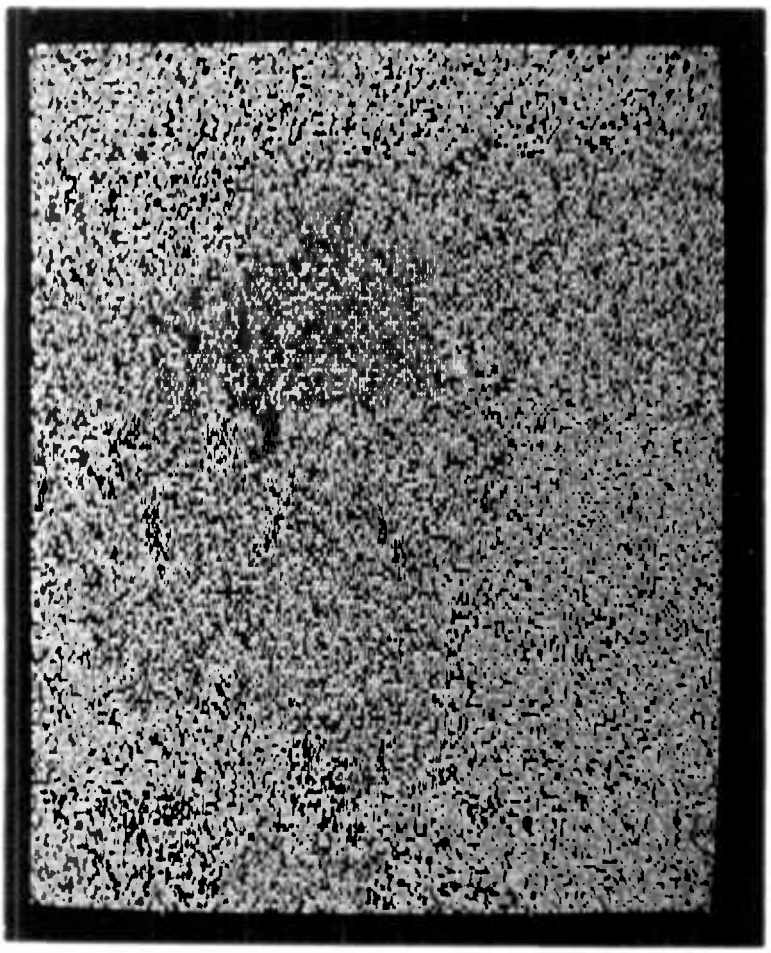
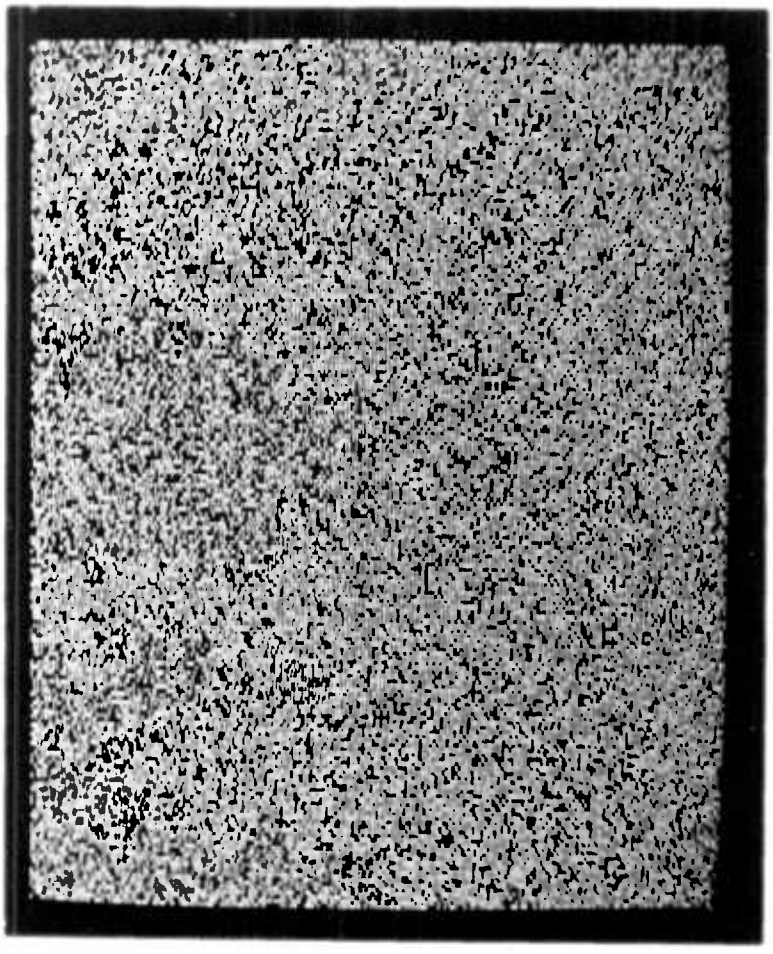


PLATE 4.9 LETTER X IN FRONT (DISPARITY 2 BITS AT 5 MHZ)



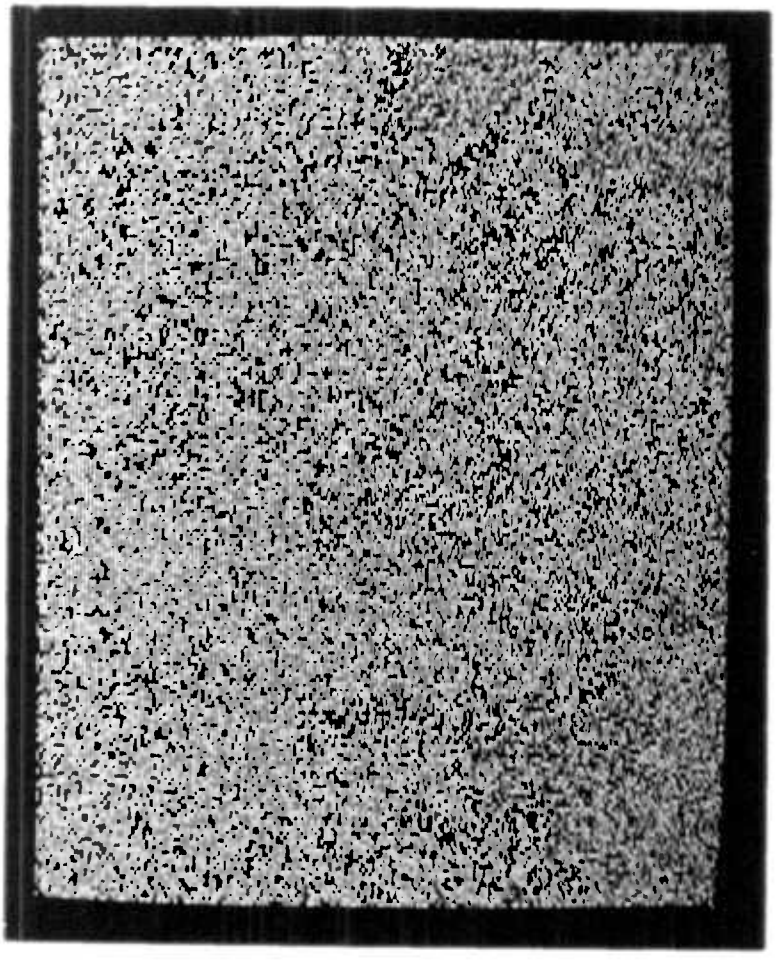
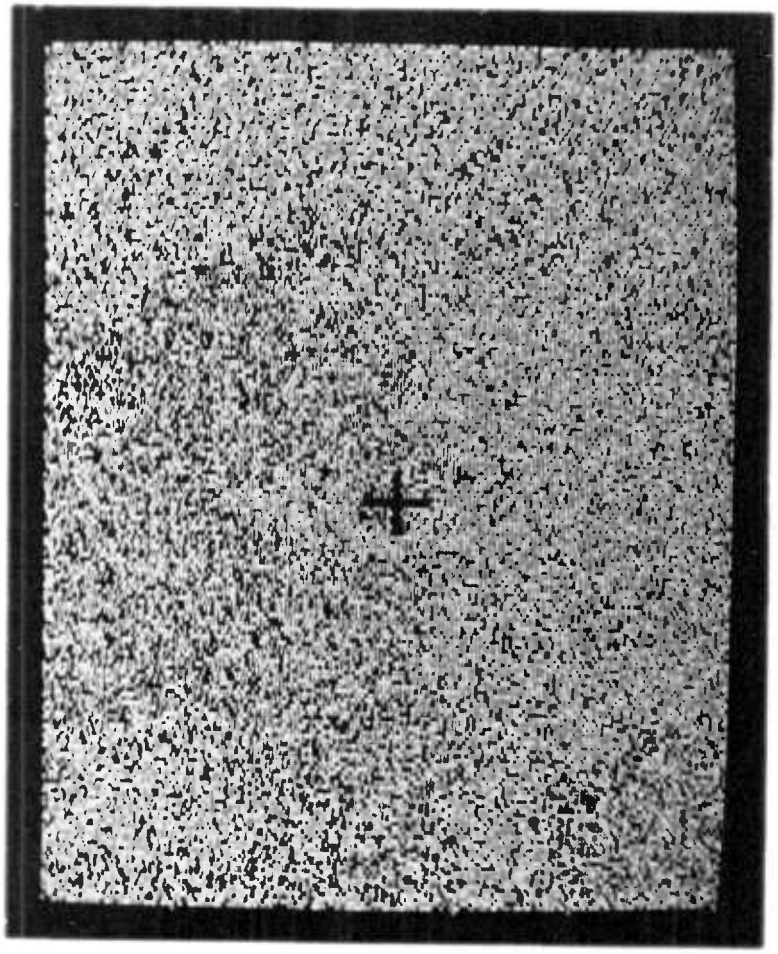
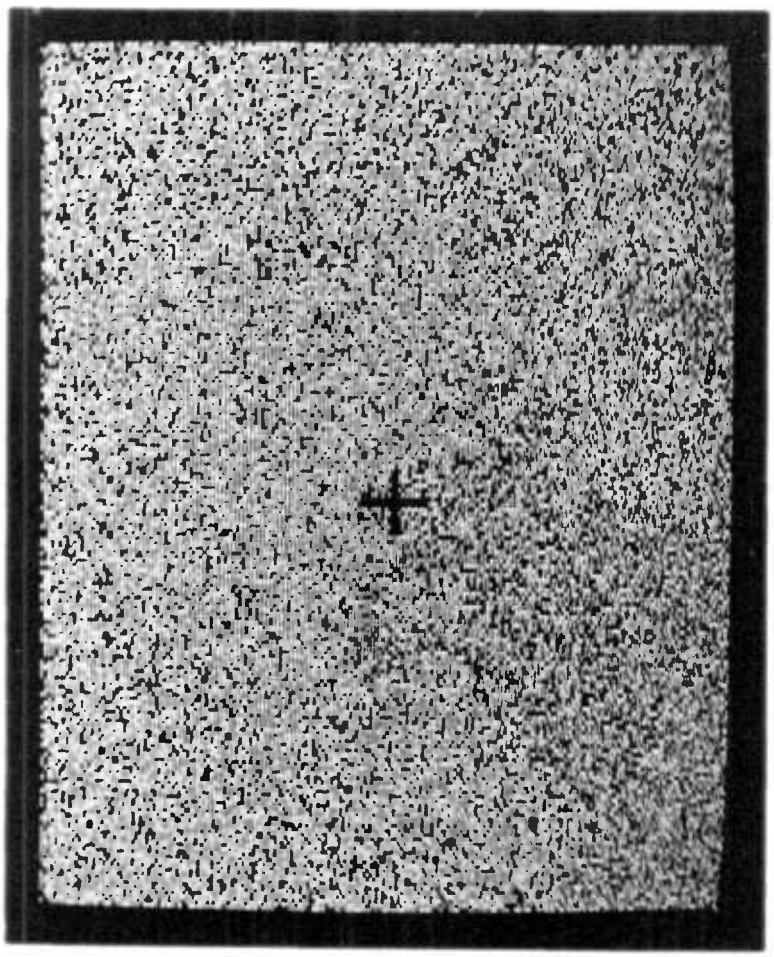


PLATE 4.IO

TOP RECTANGLE BEHIND, BOTTOM RECTANGLE IN FRONT. (DISPARITY 3 BITS)





CHAPTER 5

CIRCUIT DETAILS.

5.1. THE SEQUENCE GENERATOR.

The sequence generator shown in Fig.5.1. has feedback taps at stages 13 and 31 which is a combination that gives a maximum length sequence (KORN, 1966). When the control pulse C1 is high the feedback combination is allowed through into the first stage of the register but when C1 falls, the feedback is blocked and a constant logical level of unity is fed into the first stage. After 31 clock pulses the generator is resting in its initial "all-one" state. The pulse C1 is normally a short pulse falling to zero at the end of each frame to set the generator back into its initial state so that a stationary picture may be obtained. With C1 constantly high a dynamic noise picture is produced. A further input C2 enables a different stationary picture to be obtained by changing the initial state of the generator. With C2 high stage eight passes its information to stage nine in the normal way but when C1 and C2 are both low then at every alternate clock pulse this passage is blocked and a zero inserted into the ninth stage. This new initial state has been shown by computer simulation to be morethan one complete frame of noise out of phase with the "all-one" initial state. Thus a new stationary picture may be obtained that is effectively independent of the original. It is essential that, for this new picture to be jitterfree, C1 is a precise number of clock pulses in length.

The 31st stage is the output of the generator (V1) and provides the basic reference plane of dots. A further shift register delays V1 to give V2. The actual delay is the binocular disparity and is selected by

decade switches as shown. Operating on two taps of this register, and using the "shift and add" property of pseudo-random sequences, gives the "independent" signal V2. V2 fills in the gap between the reference plane and the shifted area which contains binocular disparity.

The sequence of random digits is contained in a rectangular area occupying most of the television screen. Figure 5.2. demonstrates how four monostables can be used to provide this rectangle. In the notation of the diagram the pulse A determines the vertical position, B fixes the rectangle's vertical dimension and C and D the corresponding horizontal dimensions.This arrangement is used to generate any rectangular shape required. Shown below the monostable chain is a circuit designed to modulate the horizontal position and this may be used in place of the third monostable. A capacitor, discharged initially at the beginning of each line, charges at a constant rate and is compared with the signal voltage. The time taken to reach equality corresponds to the horizontal position. This technique may be used to vary any dimension according to some prescribed function.

5.2. THE SHAPE OF THE STEREOSCOPIC STIMULUS.

The shape of the "in-depth" area may be a rectangle internally generated as described above or may be derived from an external video-signal. Fig. 5.3. shows the level detector used to operate on a video signal so that the boundaries of a black object on a white background may be found. VR2 is varied to bias the MC 1510 integrated amplifier, which has a flat response from d.c. to about 40 MHZ, so that the video is amplified whilst the sync. pulses are clipped. A Schmitt trigger then level detects the amplified signal. VR1 sets the gain of the system.

Whatever the origin of the signal defining the shape of the

"in-depth" area it triggers the circuits shown in Fig.5.4. which produce the binocular disparity. Waveforms for a vertical bar occupying about a $\frac{1}{3}$ of the screen are shown. The rising and leading edges are first separated by unilateral differentiators whose outputs set separate bistable latches. The counters are driven by the system's operating clock pulse and, on the setting of their controlling latch, count to the required binocular disparity set by decade switches which tap off the decoder's outputs and reset the latch. Finally three waveforms are obtained which mark out the regions where V1, V2 and V3 belong. Multiplexing to produce the final picture is performed as shown in Fig. 5.5. The first three flip-flops are required to synchronise the waveforms with a clock 90^{o} out of phase with the main clock so that as the mixed output passes into the final flip-flop, which provides the one bit delay necessary to cut out visual "crosstalk",signal changeover occurs when the main clock pulse is low. Failure to do this causes erratic working in this flip-flop and a monocular cue as a switching line is visible. Switches K1, K2 and K3 enable the three regions of the dot pattern to be blanked out so that a check may be made on the constitution of the picture and so that the size and position of the "in-depth" area may be adjusted in an experiment without the need for binocular viewing. Not shown in Fig. 5.5. is an output for the experimenter's monitor with V3 always removed to facilitate such adjustments.

The output from the T.T.L. passes into the video amplifier, also shown in Fig.5.5., whose purpose is to match the impedance of the signal source to that of the coaxial cable. This is essential as reflections on a picture of such density of detail as a random dot pattern show up readily on the monitor. A feature of this amplifier is the possibility of adding further amplitude modulation on the video signal. The brightness

of the dots may be varied over the total picture to yield a faint signal embedded in noise. Naturally, the other half of the stereo pair, consisting of V1, is amplified in the same way. Coarse and fine adjustments to the gain of the amplifier are made with VR1 and VR2 respectively.

5.3. TIMING THE STIMULUS.

In order to present the stereoscopic stimulus for a precise number of frames the frame counter of Fig.5.6. was used. Its range is 1 to 99 frames which is 40 milliseconds to almost four seconds. Because of difficulties arising from timing with interocular delay it is necessary to uniquely identify the beginning of each frame instead of merely dividing the field wave by two. The method for doing this is shown on the bottom of Fig.5.6. When the beginning of a field occurs with the beginning of a line the flip-flop is cleared and this defines the start of a new frame.

The method of presentation involved in most of the experiments perfomed was for the experimenter to give the subject a warning buzzer lasting about one second after which the stimulus would appear. Actually, the time interval between the end of this warning and the onset of the stimulus could lie anywhere between zero and 40 milliseconds because of the quantisation in television frames. This was not thought to be of any importance.

At the end of the buzzer the latch governing the counters is reset, so clearing its connected flip-flop which then awaits a frame pulse to enable the counters to count. The second frame pulse is the first that is registered in the counters. When the decoders signify the required frame number has been reached both bistable latches are reset and the

initial situation is repeated. The output is obtained from the flip-flop controlling the counters.

5.4. IMPLEMENTATION OF INTEROCULAR DELAY.

Figure 5.7. shows the general scheme adopted. A second pseudo-random sequence generator with identical configuration to the first is required which is controlled separately so that it may be set to some precise phase relation to the first. Two control pulses are produced, to set the initial states of the sequence generators. The first is in step with the television sync.pulse generator and denotes the start of each frame; the second has the same pulse width and frequency but is out of phase. These two pulses are switched between the sequence generators (Fig.5.7) depending upon not only which eye should receive a delayed version of the stereoscopic stimulus but also whether this stimulus should be behind or in front of the reference plane of dots. This is because the first sequence generator is always used to produce the pattern b in Fig.4.2. so that the bottom half of Fig.5.1. need not be duplicated. This means that when the first sequence is delayed the boundaries of the "in-depth" area must also be delayed. Since the line synchronisation is the same for the standard picture and its delayed version, this internally generated stimulus only requires an out-of-phase field pulse for it to appear out of phase. If a general shape is required so that a camera must be used then the synchronisation of this camera must be altered so that it is always in step with the first sequence generator. A second rectangle to enclose the dot pattern must also be produced and again this is done by triggering a monostable chain, as shown in Fig.5.2., with an out of phase field pulse. The two rectangles are switched by switch 2 in

Fig. 5.7. and then gate the random sequences so that the same area of each monitor is filled by random dots. Before each experiment these two rectangles had to be set up for identical dimensions by varying the pulse widths of the monostable chain. Switch 4 in Fig.5.7. switches the signals derived from the two sequence generators between the two video amplifiers and monitors depending upon whether the stereoscopic stimulus should be behind or in front of the reference plane of dots.

Figure 5.8. shows the circuitry required for producing a delayed version of the field wave. If an interocular delay of an even number of fields is required it is only necessary to delay the field pulse by an integral number of lines between 0 and 312. If, however, an odd number of fields is included in the delay the required delay is greater than the field period. Account is taken of the fact that an even field pulse is distinguished from an odd field pulse by its phase relation to line synchronisation. Therefore, instead of integral number of lines less than 312, an integral number plus one half a line up to $312\frac{1}{2}$ is counted out when the interocular delay contains an odd number of fields. In Fig.5.8 the input is a field pulse and is differentiated to set a bistable latch controlling two four-bit ripple counters whose clock pulse is 2.5.MHZ. Another bistable latch in the lower half of the diagram is set by the same input and this allows a flip-flop to accept a clock input of line pulses. At the arrival of a line pulse the upper counters lose their 2.5.MHZ input and the three decade counters below count out line pulses to the required number. The lower bistable latch is then reset and the 2.5 MHZ wave is then allowed back into the upper counters. These counters either go as far as 160 which is 64 microseconds or 1 line or 240 which is 96 microseconds or $1\frac{1}{2}$ lines. The choice is determined by

switch S1 which is set according to whether the delay is an even or odd number of fields. When this count is finished the system is completely reset and may accept a further input. The timing output is taken from the upper bistable latch and is always an integral number of lines or half lines irrespective of where the input lies with respect to the line synchronisation.

The output of Fig.5.8. provides, with its falling edge differentiated, the field control for the monitor which displays a delayed picture. A number of adjustments must be made to the standard monitor to facilitate this. In the normal way field information is extracted from the sync. pulses by a simple low pass filter which is then connected to the input of a blocking oscillator. The latter connection must be broken and instead a pulse of similar height and width inserted to give the new field information. This is shown in Fig.5.10. The normal sync. pulses must be replaced by a signal consisting only of line pulses. If this is not done, any slight loss of synchronism of the line blocking oscillator occurring during the original field blanking period results in binocular disparity between the two monitors and produces a horizontal bar of dots outside the reference plane of dots.

An out of phase frame pulse to control a sequence generator is produced in a similar way to the field pulse delay shown in Fig.5.8. The only difference is that the upper counters always count to exactly one line and the lower counters may be set to any number up to 624. The rest of the delay is produced as shown in Fig.5.9.

The latch L_4 determines whether a stationary or dynamic picture is obtained. If it is set so that A is high, then with the flip-flop receiving as a clock input short frame pulses the flip-flop's output Q is high and

the frame pulses are let into latch L2. This latch is reset by two four bit ripple counters and the latch output thus produces the short accurately timed pulses which control the sequence generators. In the lower half of the diagram the system is duplicated but the latch L3 is set by delayed frame pulses which are gated not by Q, the output of the flip-flop F, but by a delayed version of this which is taken from a shift register clocked at the frame frequency.

When the latch L1 is reset Q falls to zero after the reset frame pulse and this blocks any further frame pulses into L2. The sequence generator that receives its control from the latch L2 is then no longer set to the initial state at the start of each frame but begins to run free. The latch L3 continues to receive delayed frame pulses until the fall of Q to zero has passed through the shift register. The sequence generator which L3 controls does not run free until this time. A phase relation between these two sequences is therefore set up which may consist of any number of frames and lines up to and including eight frames (with the eight-bit register used). The input to L1 may be from a manual switch or can be a timing pulse derived from the frame counter so that the sequences run free at the time that the stereoscopic stimulus is presented.

There are some minor complications that arise in order that the stereoscopic stimulus is presented without any monocular cue. If the changeover from pattern a to pattern b (Fig.4.2) occurs in an already dynamic picture then it is only necessary to ensure that this changeover occurs in the monitor's field blanking period. If the first sequence generator is lagging behind the second then the timing pulse from the frame counter must be put in step with the former by the circuit in Fig.5.11(a). When the subject is presented with a stationary pattern which then changes

to dynamic noise with interocular delay it is necessary to change from pattern a to pattern b just before the first frame that is different from its predecessor. If sequence 1 leads sequence 2 then the waveform to perform the pattern change will be Q (Fig.5.9.) delayed by one frame as shown in Fig.5.11(b). This is because the picture is stationary for one frame after Q rises. When sequence 1 lags behind sequence 2 then it will be necessary to differentiate between a delay of an even and an odd number of fields. If the delay is an even number then the waveform to switch from pattern a to pattern b will be obtained by delaying S (Fig.5.9) by one field and then passing the output into the circuit of Fig.5.11(a) for a further delay of less than one field. If the delay is an odd number of fields than S is delayed by one whole frame before passing into circuit a (Fig.5.11). This is shown in Fig.5.11(c) where S1 is the same switch used to distinguish between delays of even and odd numbers of fields used in Fig. 5.8. With these arrangements there is never any monocular cue in the presentation of the stereoscopic stimulus to the subject.

5.5. THE FIXATION POINT.

Figure 5.12 shows the scheme for the production of the fixation point. There are six measurements to be defined. Vertical dimensions are all integral numbers of lines whilst horizontal dimensions are integral numbers of 2.5. MHZ bits. This ensures that the fixation point will fit exactly into the grid system already in the random dot pattern. The fixation point may be made up of white dots or black dots but normally black was used. Binocular disparity is added by a shift register clocked at the frequency of the random dot pattern. All six dimensions were

variable; v and h could be set (Fig.5.12) to two decimal places whilst all the rest could be fixed to one decimal place. For the vertical dimensions in Fig.5.12, a wide field pulse triggers v which in turn triggers t at its completion time preventing itself from further generation in that television field. The outputs m and t are then mixed with w and u which are produced in a similar way to give the fixation point as shown.

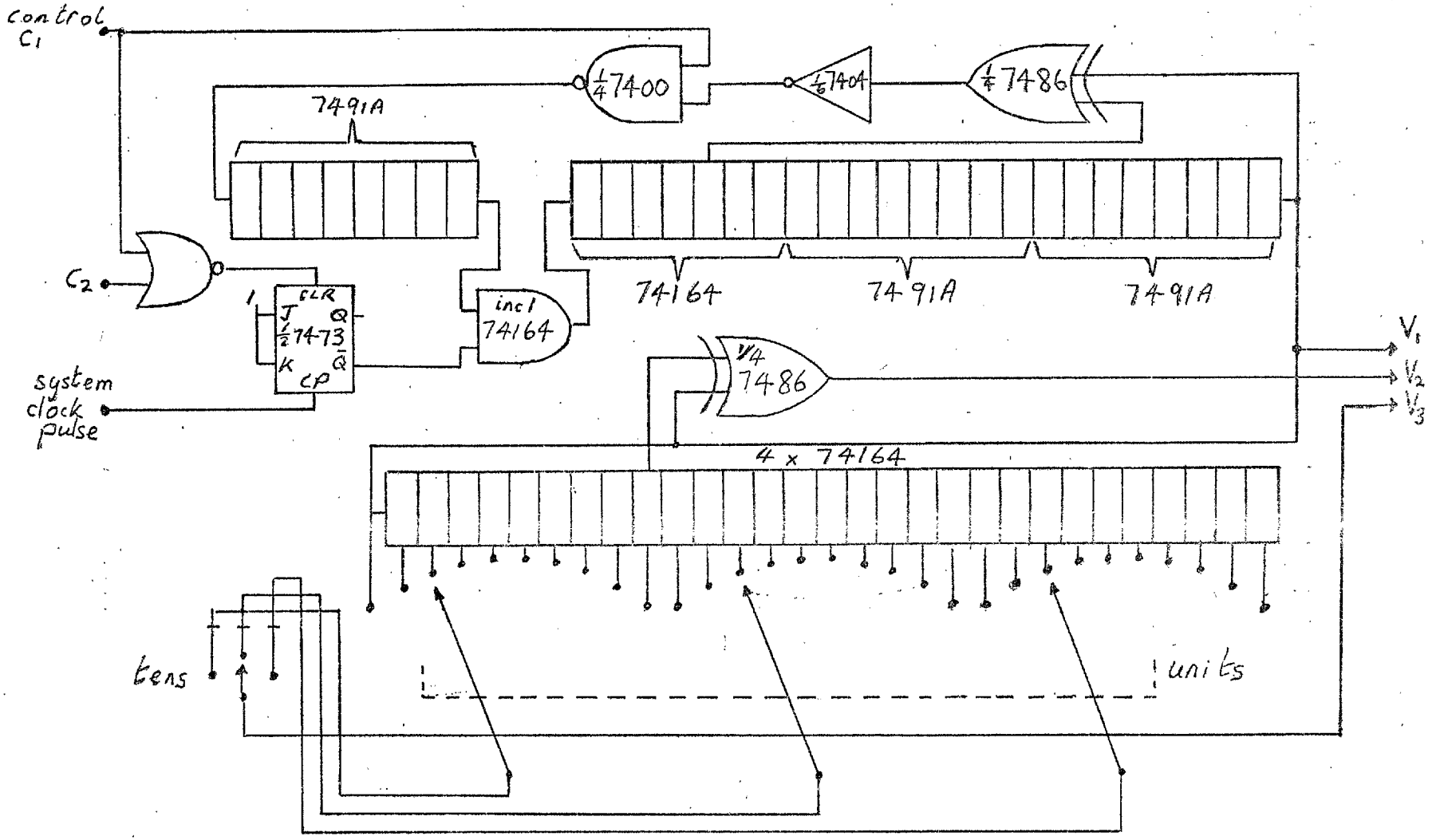


FIG.5.4 GENERATION OF JULESZ PATTERN COMPONENTS

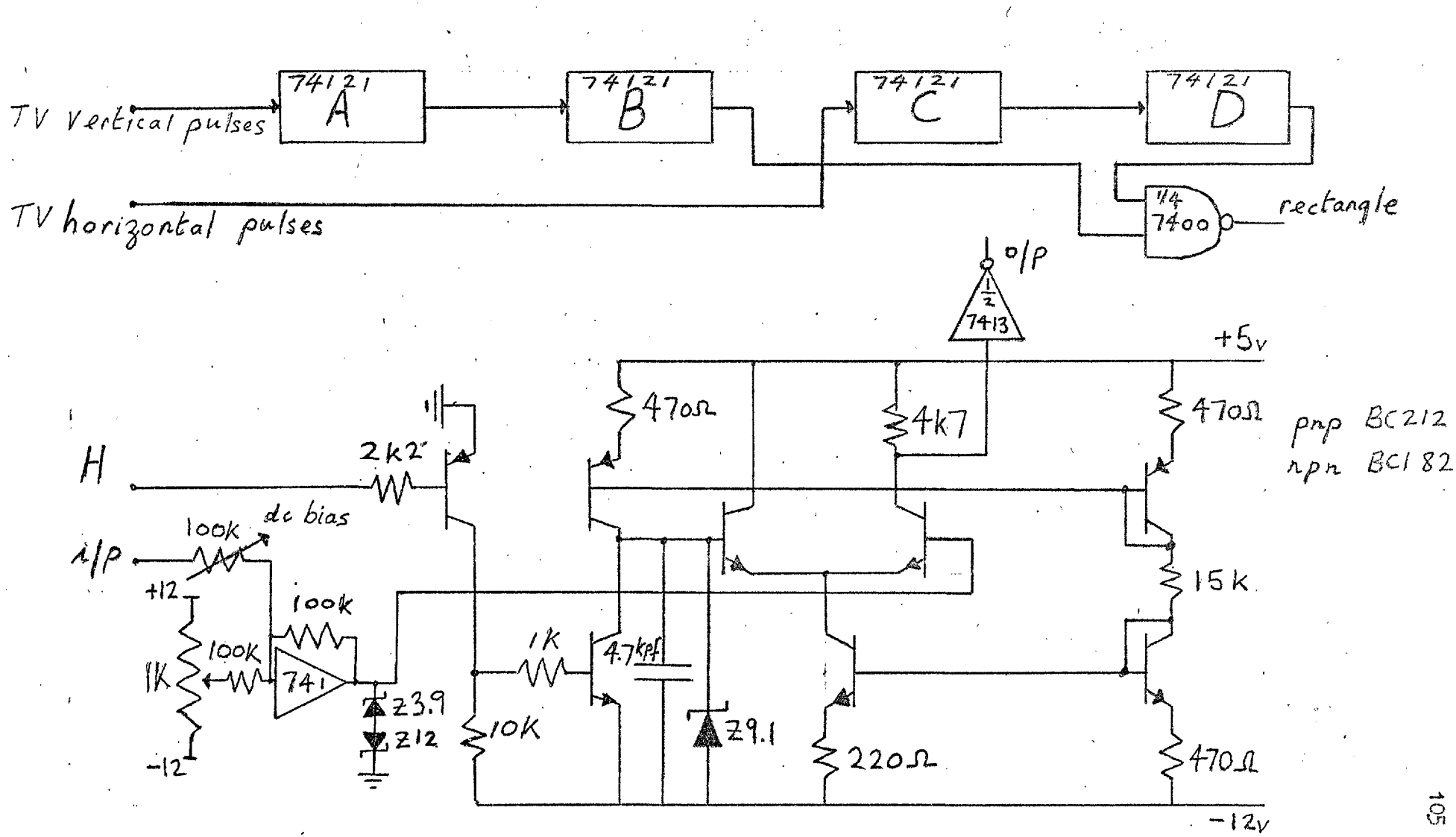
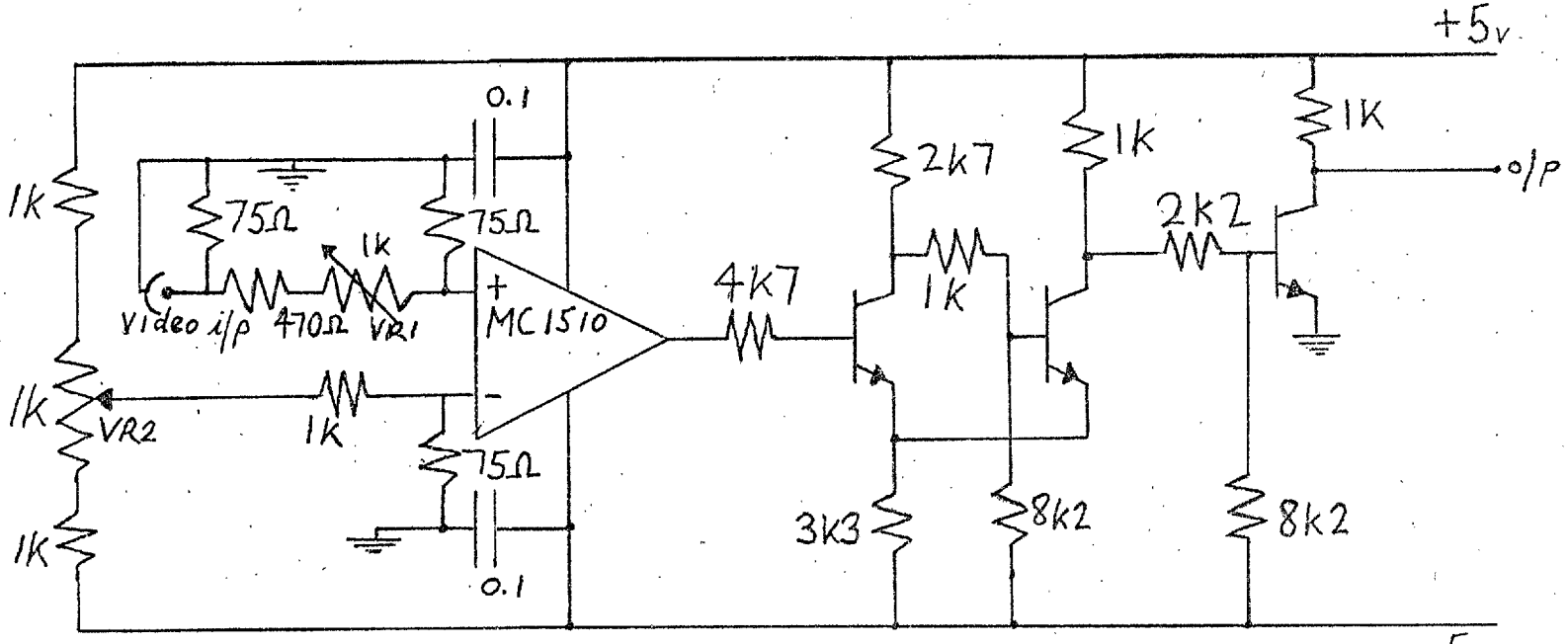
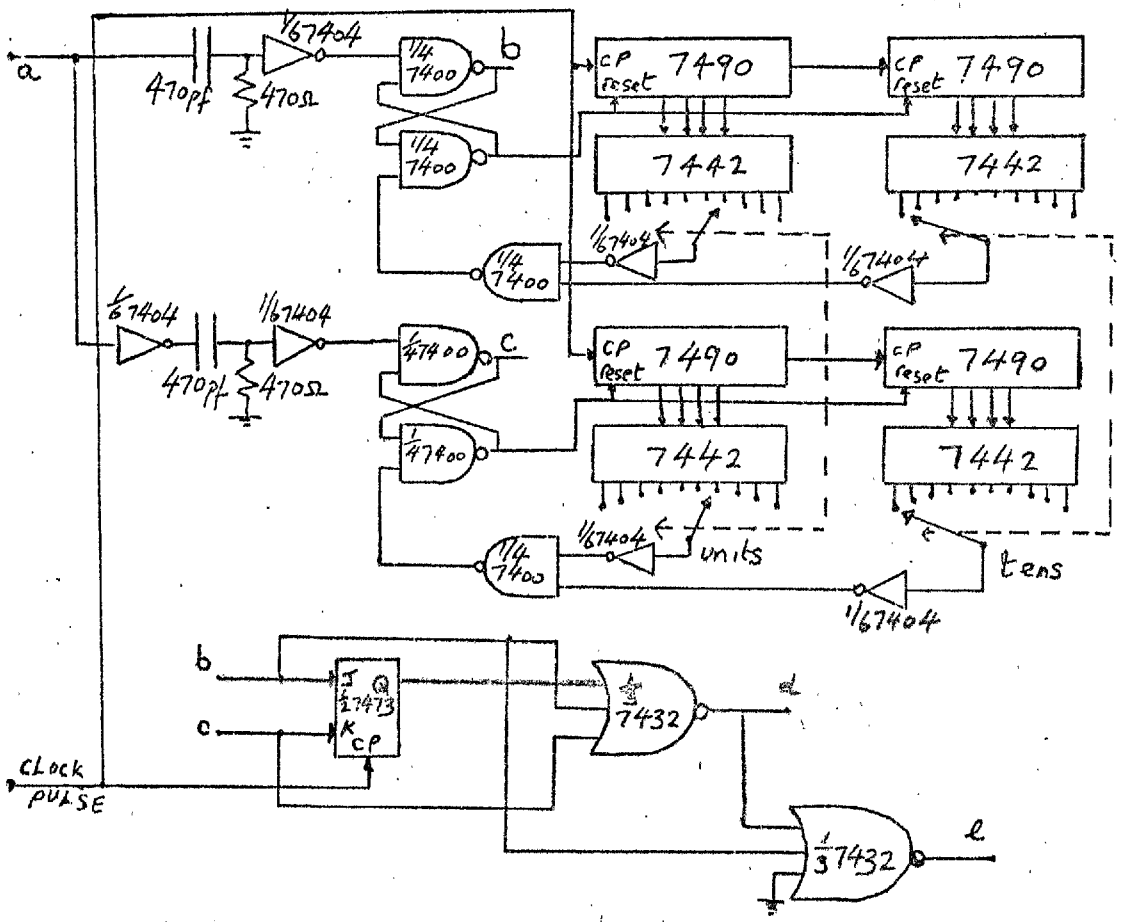


FIG. 5.2 MODULATION OF THE DIMENSIONS OF A RECTANGLE ON A TV SCREEN



ALL TRANSISTORS TIS46

FIG. 5.3 VIDEO LEVEL DETECTOR



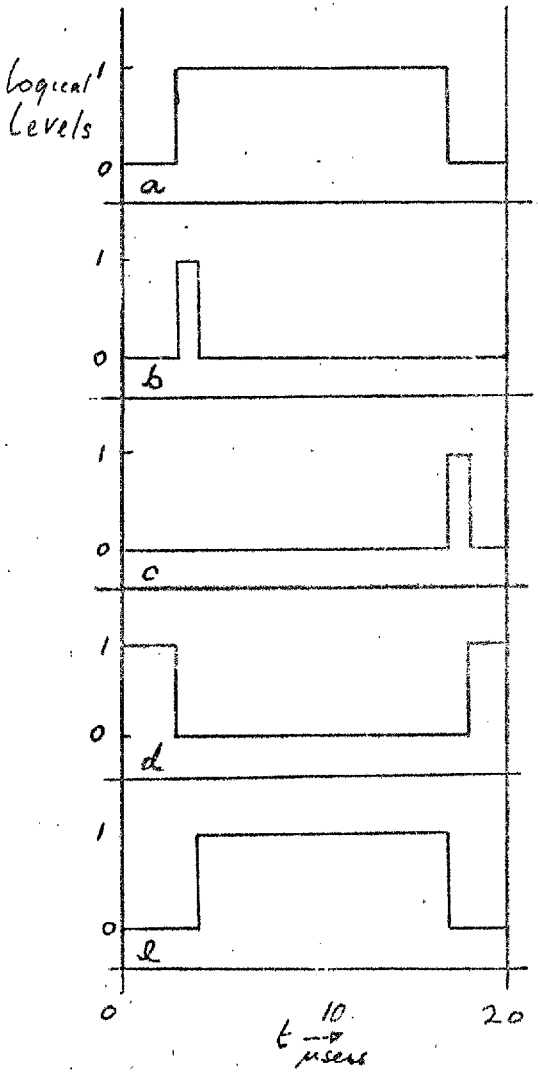
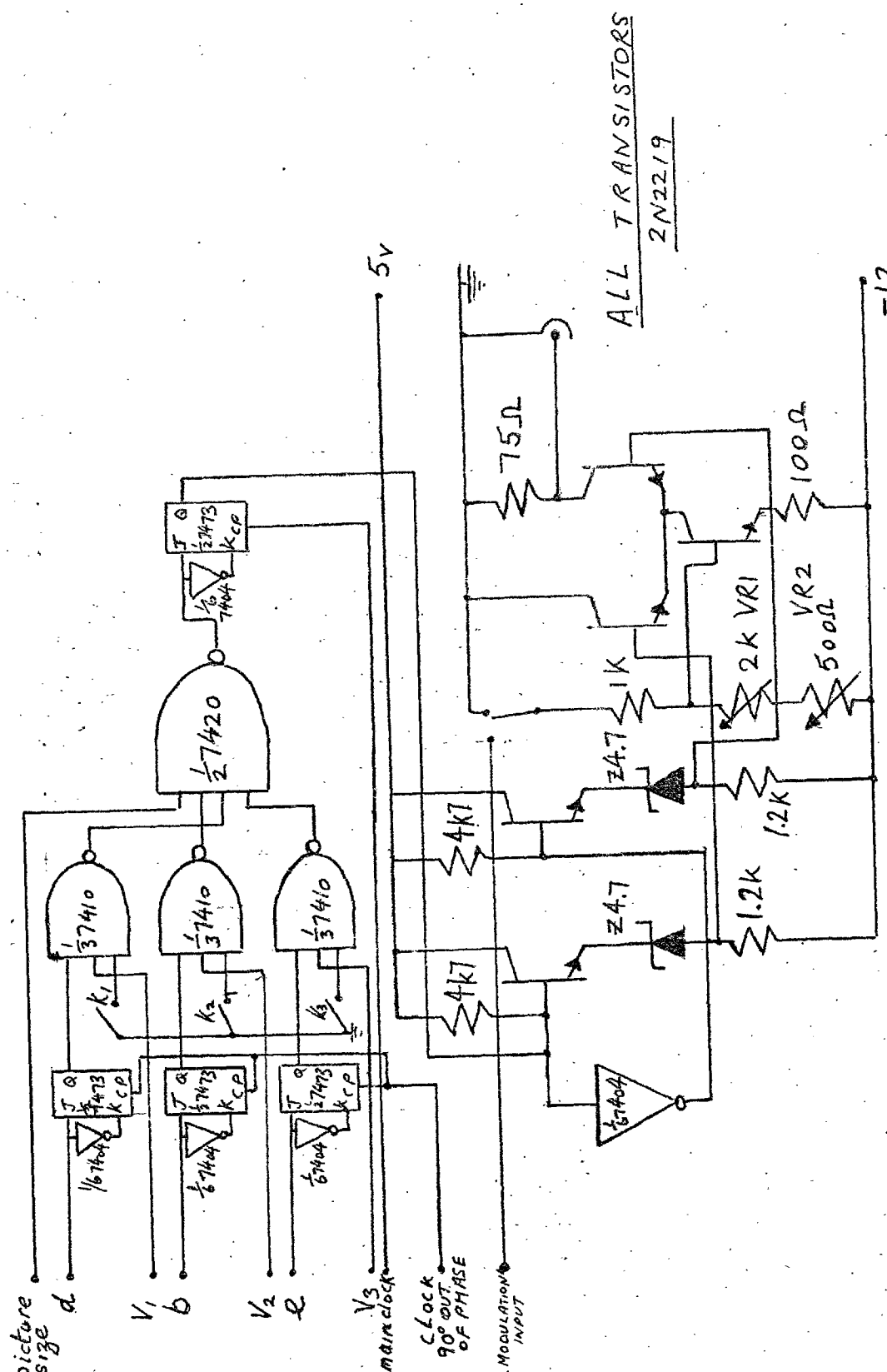


FIG. 5.4. VARIATION OF BINOCULAR DISPARITY

FIG.5.5 MULTIPLEXING AND FINAL AMPLIFICATION



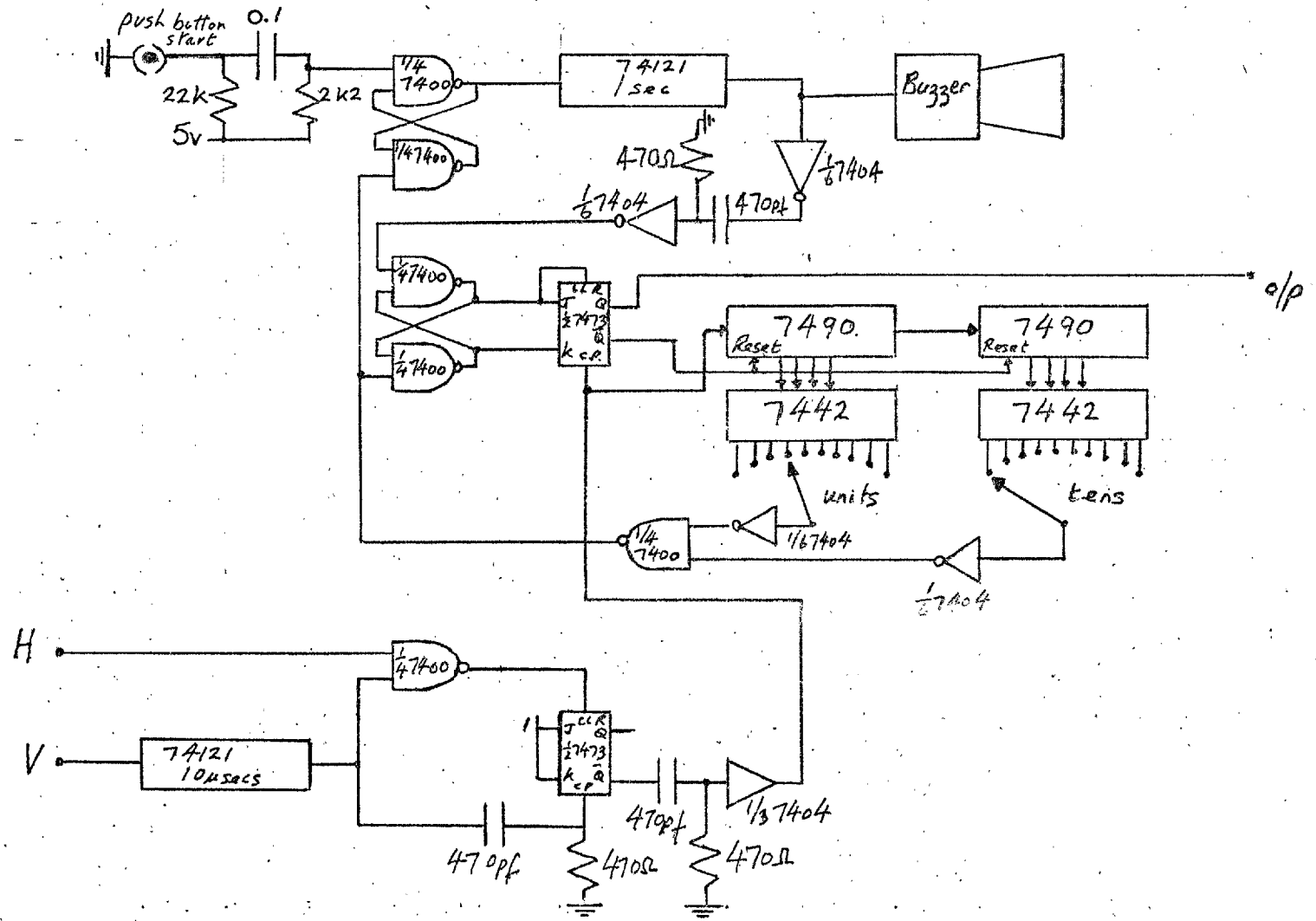
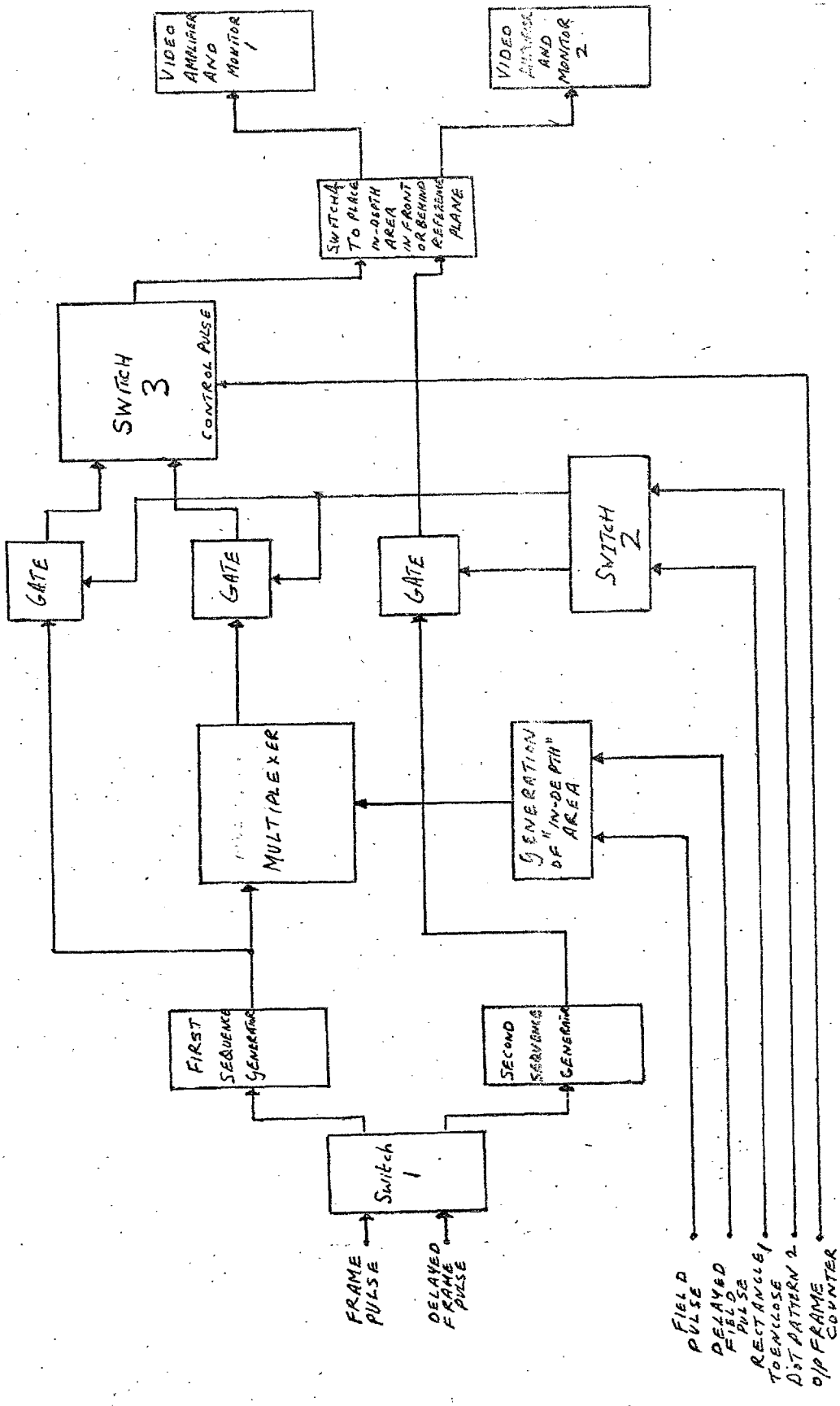


FIG. 5.6 FRAME COUNTER

FIG. 5.7 SCHEMATIC DIAGRAM OF SYSTEM



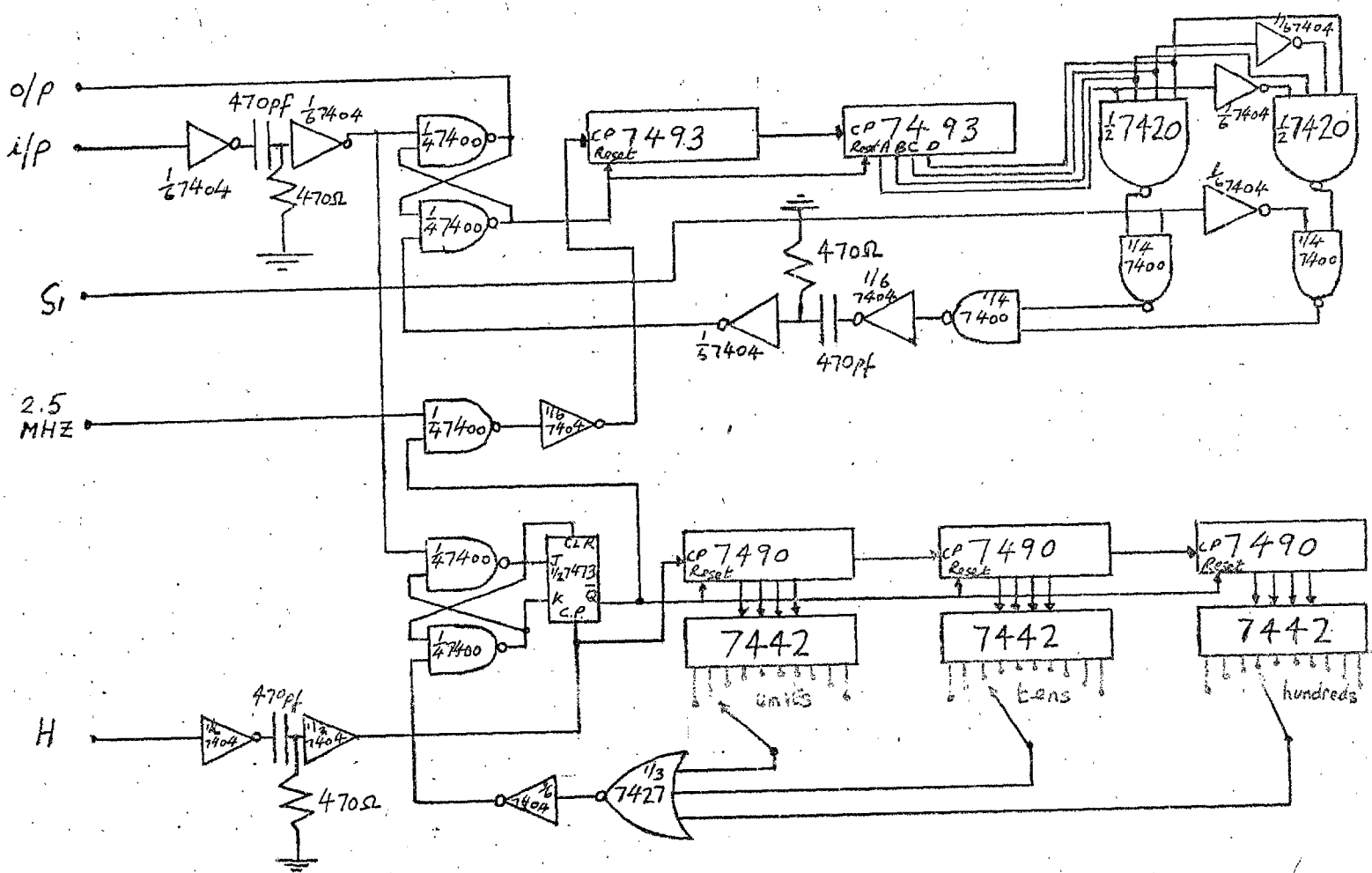


FIG. 5.8 PRODUCTION OF DELAYED FIELD PULSE

FIG.5.9 PRODUCTION OF A DELAYED PULSE FOR THE CONTROL OF A SECOND SEQUENCE GENERATOR

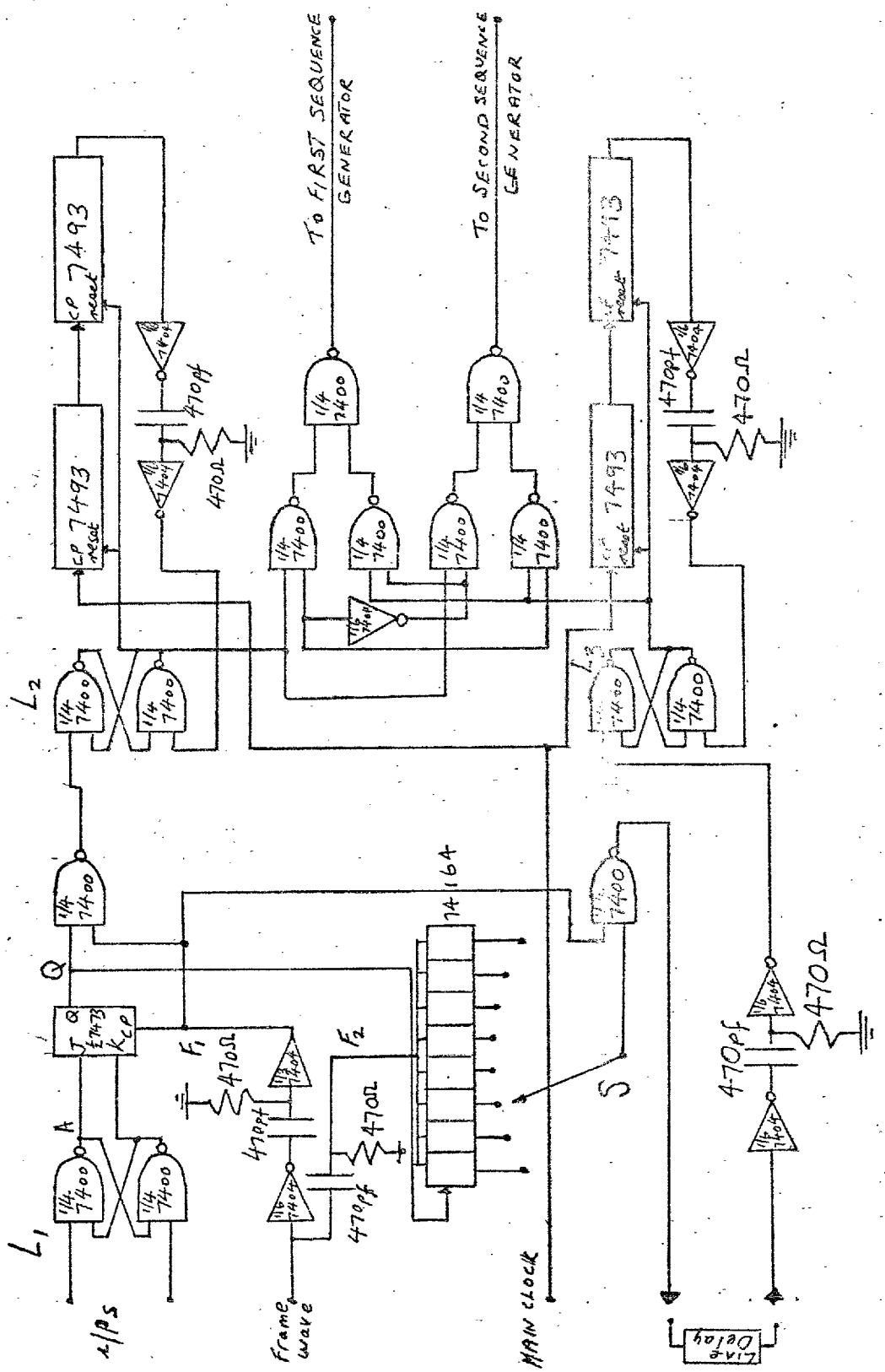


FIG. 5.10 SYNCHRONISING THE FIELD SCAN OF THE VIDEO MONITOR

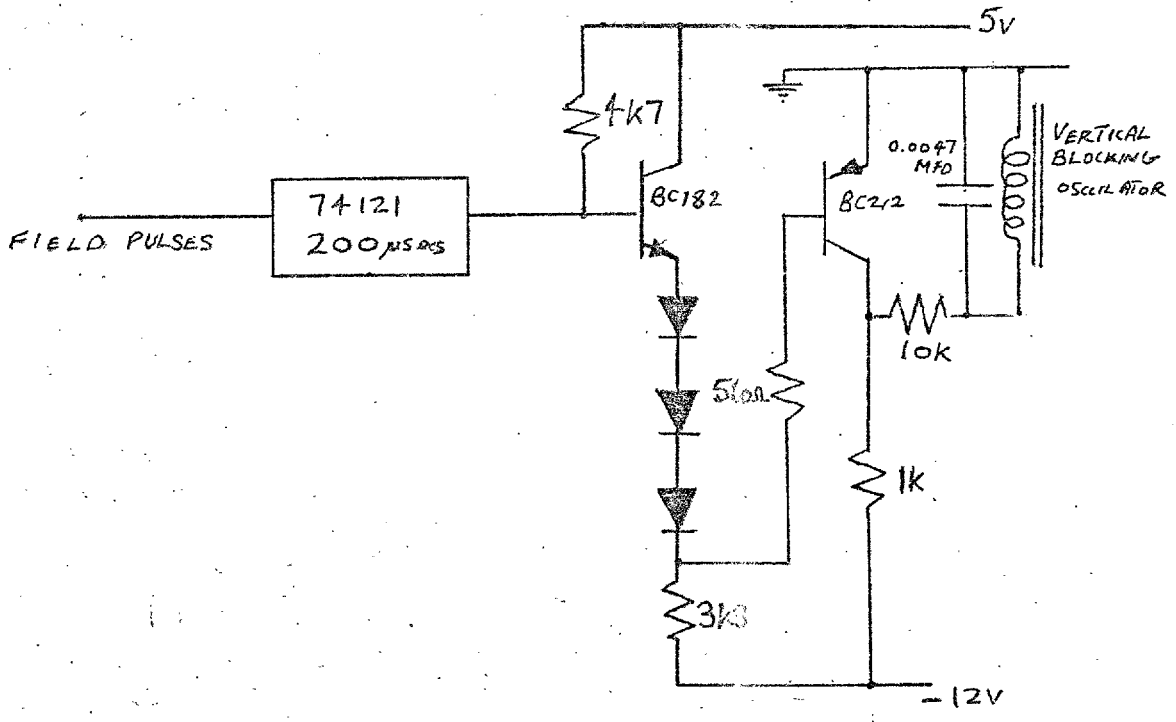


FIG. 5.11 ADJUSTMENTS TO THE TIMER WHEN INTEROCULAR DELAY IS USED

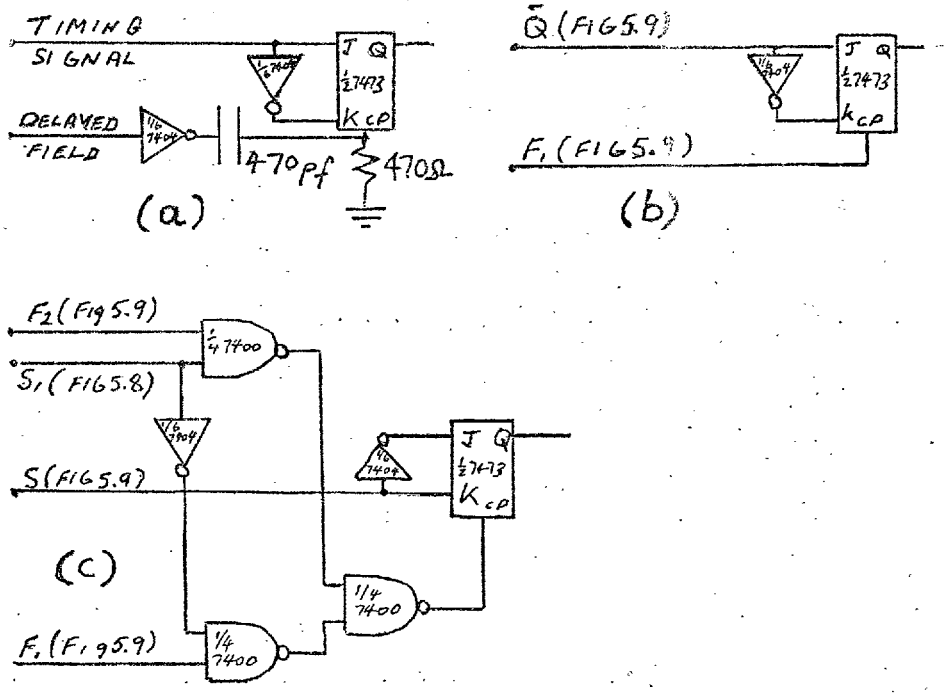
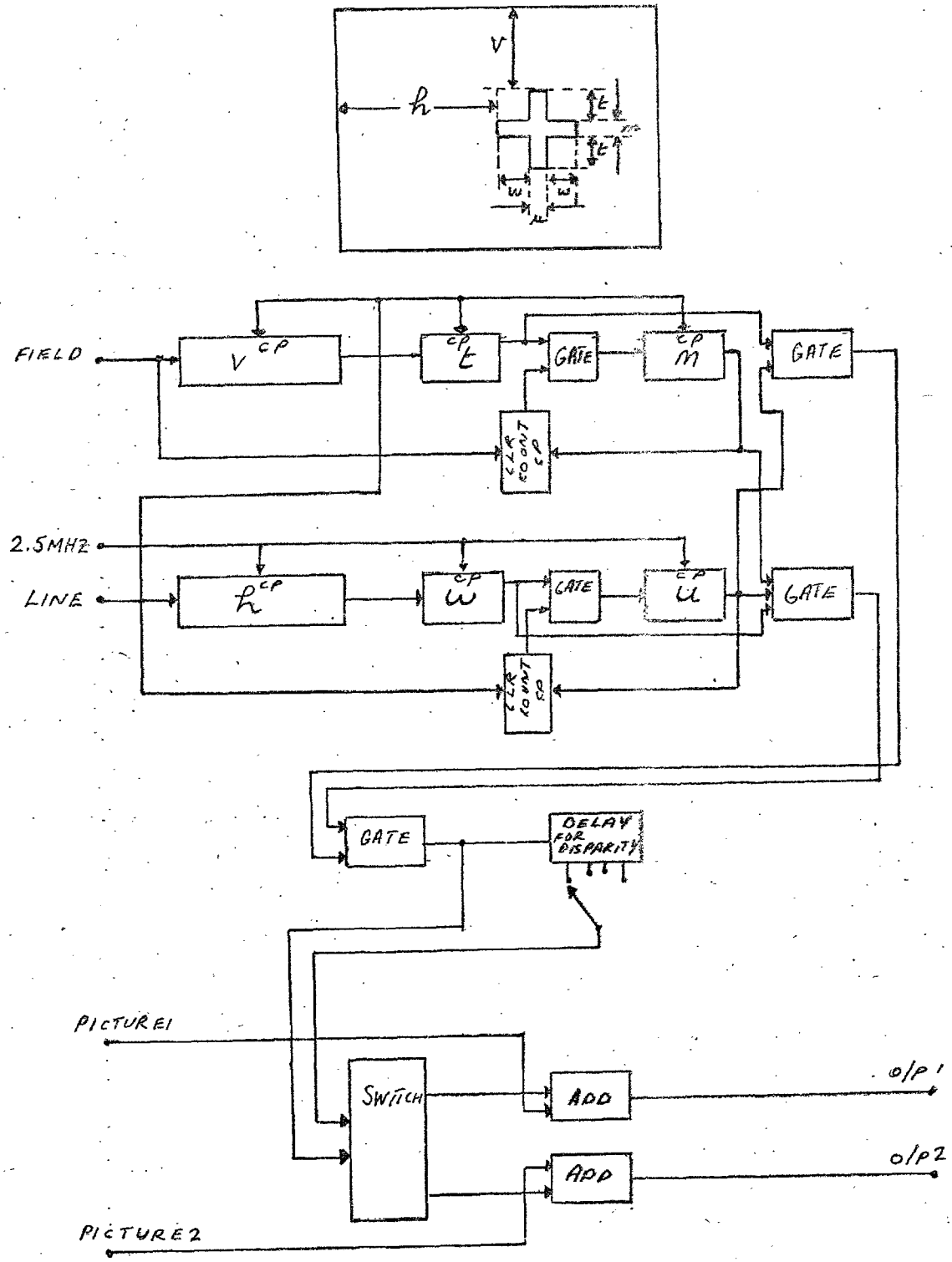


FIG.5.12 PRODUCTION OF FIXATION POINT



CHAPTER 6

PRELIMINARY EXPERIMENTS.

6.1. INTRODUCTION.

Before proceeding to describe experiments conducted by the author some observations may be made on the use of visual noise in perceptal research. Visual noise is rich in features and therefore may be expected to excite even if only incompletely, most of the feature extraction systems in the brain. The orthogonal afterimages of McKay (McKAY, 1961, 1965) are an example of this. An observer, after adaptation to a stimulus consisting of radial lines, sees on transferring his gaze to visual noise the orthogonal pattern of concentric rings superimposed on the noise. Visual noise in this case does not excite all detectors equally because the feature extractors responding to radial lines, having formerly been excited to a greater degree than others, become less sensitive and give less output to an equal stimulus than those feature extractors detecting the orthogonal pattern of concentric rings.

Moiré patterns produced entirely by random dots were first reported by Glass (GLASS, 1969). This may be observed on the author's apparatus by removing the viewing polaroids and shifting one of the TV monitors so that its picture is not seen exactly superimposed on the other. Moving Moiré patterns may be observed with dynamic noise. In this case the noise appears to "stream off" into a variety of channels. As a phase change (temporal) is introduced between the pictures the "streams" of noise appear to flow more sluggishly giving a "treacly" texture. As the delay is increased beyond a critical point, this treacly texture disappears and any further delay between the pictures produces no change in the appearance of the noise which is now as if the visual noise displayed on the monitors is

derived from two independent sources. At a delay below this critical point apparent motion between the two superimposed noise patterns is perceived. The apparent speed is then inversely proportional to the delay. When the delay approaches the critical limit, which depends upon the separation by the two superimposed pictures, apparent motion is lost.

When a random dot stereogram consisting of dynamic noise is viewed, the area containing binocular disparity is seen as a sheet of swirling dots. These swirling dots do not change depth planes. If one of the planes is a ring then the swirling dots may sometimes appear to move around the ring.

Small areas in the stereogram of binocular disparity are difficult to see in a stationary dot pattern but may become cleaner when the stereogram is made from dynamic noise. Small clusters of dots may have, by chance, identical zero as well as non-zero binocular disparity and the brain must resolve this ambiguity. When the stereogram is made of dynamic noise then each frame of dots is an independent sample and the brain is then provided with a continual supply of evidence to resolve the ambiguity.

If an area in one component of a random dot stereogram is replaced by an entirely independent dot pattern binocular fusion of the two patterns yields a "hole" in this area if the patterns are of stationary dots. Since there is no regular disparity for this area, clusters of dots form at varying depths but all further from the observer than the reference plane. This seems to agree with Julesz's rule for (JULESZ, 1971) the location of the dots in the ambiguous area of a normal random dot stereogram. Solutions which place these dots further from the observer are preferred to those which place them nearer. When the experiment of fusing independent patterns is repeated with dynamic noise then clusters of dots are not seen moving in depth. The "hole" effect disappears and the independent noise is seen in the same plane as the reference plane though the difference in texture

between the area of independent noise and the rest of the picture is evident. The special area is less clearly defined and the movement of the dots less sharp. The failure to see clusters of dots jumping between depth planes when dynamic noise is used is evidence of the time required by the brain to solve the depth location problem when there is no regular disparity. Every frame would yield a different solution and each would be independent of the next so that a solution cannot be reached after several frames but must be found separately for each new frame.

Of the experiment to be described in this chapter Test 1 and 2 compare the various ways of presenting a stereoscopic stimulus for a short time to a subject. Tests 3 - 6 investigate binocular fusion in the centre of the visual field as disparity, the time of presentation and the size of dots are varied.

6.2. EXPERIMENT 1.

Ten subjects were used for this test, each subject being presented with four treatments of ten samples each. The subject was shown a random dot stereogram for 80 milliseconds which contained a rectangle at a convergent disparity. The rectangle was either aligned with its longest side vertical or its longest side horizontal and the subject was asked to discriminate between the two. This method of shape discrimination for testing stereoscopic fusion has been used by Durnford in tests on hemispherical dominance (DURNFORD & KIMURA, 1971). In the author's experiment photographs of the rectangle in its two positions were made and the transparencies presented to a TV camera by a TV slide viewer (Philips type8400). After level detection of the camera signal the same shape appears in the random dot stereogram.

In treatment1 the subject viewed a stationary random dot pattern with

all the dots in one plane. The rectangle was presented by an area in the left eye's pattern shifting to the right to give a rectangle of dots with a convergent disparity. The right eye's pattern remains stationary through out.

In treatment 2 the subject viewed a blank screen with an illumination equal to that present when the random dot pattern was presented. This was shown for the same time as in treatment 1 but now the left eye's monocular cue does not exist. Treatment 3 was the same as treatment 2 except that the two frames that contain the stereogram have independent dot patterns each displaying the same shape at the same disparity.

In treatment 4 the subject viewed a dynamic noise pattern with all the dots in one plane. The stimulus was presented as in treatment 1 but the left eye does not see the shift of the rectangle area since each frame of dots is independent of the next.

A one second buzzer warned the subject of the onset of the stimulus. After making his decision he pressed one of the buttons on a keyboard in front of him. This lit up a number tube located near the experimenter and also one by the keyboard so that the subject could check what he had pressed. The code for correcting the subjects answers into numbers was clearly written on the keys. After recording the subject's answer the experimenter cleared the number tube and proceeded to arrange the next display. By an extra light indicating an error, provision was made for the subject to change his answer if he should press the wrong key by mistake. The subject and the optical equipment were in a room 10' by 12' with an illumination much lower than that of the TV monitors. A small light illuminated the keyboard after each stimulus and was turned off when the number tube was cleared. The experimenter and the electronic equipment were positioned outside the experimental room. There was no verbal communication between the subject

and experimenter once the subject had entered the experimental room.

The subject was presented with the ten samples for each treatment before moving on to the next treatment. The order in which he was subjected to these treatments was randomised for each subject as was the sequence for an individual treatment.

The results for Test 1 are shown on Fig.6.1. A t test with 9 degrees of freedom reveals that only in the case of treatment 1 and treatment 4 is the average score significantly better than that which could be obtained by chance. A further comparison shows that the score for treatment 1 is significantly better than that obtained under treatment 4.

Subjects distinguished between the two rectangles on the basis of the area showing binocular disparity relative to the reference plane. From the results it would appear that this relative disparity is more readily deciphered when the observer views the reference plane of dots before the appearance of rectangle as in treatments 1 and 4. In addition the subjects found the task easier when the pattern remained stationary with a monocular cue displayed when the rectangle appeared, than when the pattern was of moving dots with no monocular cue in the presentation of the rectangle. It would seem that the monocular cue was a significant aid. Experiment 2 was designed to confirm this.

6.3. EXPERIMENT 2.

In this experiment treatment 1 was the same as treatment 1 in Experiment 1. In treatment 2 the subject looked at a stationary dot pattern which changed to a new independent dot pattern when the stimulus was presented. In this way the monocular cue of treatment 1 was removed but the texture and brightness of the pattern before and after the stimulus was presented were identical.

Eighteen subjects were used for this experiment. The test stimulus was a square in front of the reference plane. A test sample of 50 was used and in half of these the square appeared after the warning buzzer. In the other half the reference plane remained as it was before the buzzer (except that in treatment 2 the plane was made up of a new set of dots). The task for the subject was to decide whether a square had appeared or not. Each subject had a different sequence in which all four types of sample(2 treatments and 2 possibilities for each treatment) appeared in random suvvession. The first ten samples were used as practice and disregarded by the experimenter. Of the remaining 40 there were 20 for each treatment of which 10 showed the square. A single frame of 40 milliseconds was used to present the stimulus. The results and a summary of the experimental conditions are shown on Fig. 6.2.

A t test with seventeen degrees of freedom indicates that the subjects were able to score at better than a chance level for both treatments. Comparing the success scores for treatment 1 and 2 by the method of analysis of variance (EDWARDS, 1970) it is found that subjects did significantly better with treatment 1 when a monocular cue was present than with treatment 2. Analysing the errors of each treatment into the two possibilities (i.e. square misteken for blank (no stimulus) and vice versa) the following is found. The error that occurs when a blank is thought to be a square is less likely under treatment 1 than under treatment 2. For treatment 1 this error is less likely to occur than its inverse. These two statements are for a significance level of 5 % and all other comparisons show a non-significant difference.

The single frame exposure made this test rather difficult though the subjects were able to do better than chance even without the monocular cue.

The latter is a positive help in attempting the task given in Experiment 2 and the absence of this cue when the picture remains staticnary makes subjects very certain that no square has been presented.

6.4. EXPERIMENT 3 AND 4.

These two experiments are the first in a sequence designed to examine the nature of stereopsis in the centre of the visual field with the aid of random dot stereograms. Experiment 3 and 4 were identical in design but 4 was performed a week after 3 in order to investigate any learning. The same twenty subjects were used in both experiments. The mode of presentation of the stereoscopic stimulus was as for treatment 2 in Experiment 2. A small black cross which was part of both television pictures was used as a fixation point and this was seen at zero disparity (i.e. in the reference plane of dots). The same square as used for Experiment 2 was used as the stimulus and this appeared either in front of the reference plane (nearer to the observer) or behind the reference plane (further from the observer) for two television frames or 80 milliseconds and the fixation point disappeared for this time. The disparity was varied from one to six bits at 5 MHZ which is a range from 3.4' to 20.4'. The square was taken with convergent and divergent disparity from inside Panum's fusional area to well outside. As double images cannot exist with random dot stereograms, stereopsis in the steady state is possible at these disparities but it is the dynamic aspects of the fusion process that are to be examined here.

Each subject was presented with a sequence of 100 samples and recorded his judgement as to whether the square appeared further or nearer to him than the reference plane of dots and the fixation point. Each subject received a different sequence in which the treatments were randomised.

The first sixteen were discarded by the experimenter. Of the remaining eighty four,each treatment,which in this case was a particular disparity, was presented fourteen times and in half of these the square was in front of the reference plane. All the subjects used were,by the time Experiment 3 was conducted,very familiar with random dot stereograms and could readily discriminate between a square in front of the reference plane and one behind.The subjects were told before the experiment was begun that the square would always appear but that the depth either in front or behind the reference plane would vary and they were then shown all twelve positions in which the square could appear. The results for Experiment 3 are shown in Fig.6.3 and a summary of the experimental conditions in Fig.6.5.

The two types of error are analysed separately. In error 1 the subject judges the square to be further from him than the reference plane when in fact it is nearer to him and error 2 is the converse case. By the methods of Analysis of Variance,Table 6.8 shows that there are significant differences between the treatments for error 2 but not for error 1. A Duncan's Multiple Range Test (EDWARDS, 1970) is performed for error 2 and theresult is shown in Table 6.9. The error increases with the disparity. Disparities 5 and 6 give the greatest errors and these are significantly higher than for all other treatments but do not differ significantly between themselves. The error for disparity 4 cannot be distinguished from that for 3 but is significantly greater than that for disparities 1 and 2. These relations are demonstrated in Table 6.7 by lines linking the disparities whose errors do not differ significantly. Table 6.12 in Fig. 6.5 shows that for Experiment 3 there is no significant difference between error 1 and error 2 for disparities 1 and 2 but for the rest error 2 is significantly greater than error 1. The reults for Test 4 are shown in Fig. 6.4 and a comparison between Tests 3 and 4 shown in Tables

6.12 and 6.13 in Fig.6.5. Tables 6.10 and 6.11 for Test 4 show similar results as their counterparts, Tables 6.8 and 6.9, for Test 3. Table 6.12 demonstrates a difference between Tests 3 and 4 for disparities 1 and 2. Whereas for Test 3, there was no significant difference between errors 1 and 2 at these disparities, in Test 4 error 1 is significantly greater than error 2. For disparities 3 - 6 error 2 is significantly greater than error 1 as it was in Test 3. In Table 6.13 on Fig.6.5 an overall comparison between the Tests 3 and 4 is made. There is no significant difference between the two tests for error 1, error 2 or for the total error.

In conclusion it may be said that Tests 3 and 4 showed that disparity did not affect error 1 but for error 2 an increase in disparity caused an increase in error. At the high disparities of 3 - 6 more mistakes of the error 2 type are made than the error 1 type. The subjects did not improve their performance in Test 4 over Test 3. The tendency to produce more type 1 errors than type 2 errors at disparities 1 and 2 in Test 4 was probably caused by a need felt by the subjects to record as many squares behind as in front of the reference plane although they were not told there was an equal number of each. It is clear that there is a tendency at high disparities to judge many squares actually behind the reference plane as in front. This tendency evidently does not disappear with practice, although no feedback was given to the subjects on their performance.

6.5. EXPERIMENTS 5 AND 6.

In Experiments 5 and 6 the disparity was kept constant but the duration of presentation was varied from a minimum of two frames to a maximum of seven frames. A clock pulse of 2.5 MHZ was used in Test 5 and of 5 MHZ in Test 6. In all other respects Tests 5 and 6 were identical to

Tests 3 and 4. The test conditions are summarised in Fig.6.9.

Table 6.14 on Fig.6.7 shows the results for Test 5. As in Tests 3 and 4 only error 2 shows a significant ratio in the analysis of variance. A Duncan's Multiple Range test performed for error 2 is shown in Table 6.15. The error decreases as the duration of exposure increases. The results for Test 6 are shown in Fig.6.8. They are qualitatively the same as Test 5. A comparison of Tests 5 and 6 is made on Tables 6.18 and 6.19. Table 6.18 shows a significant tendency to make more type 2 errors than type 1 errors up to dureation of 4 to 5 frames or 160 to 200 milliseconds. Table 6.19 shows that an increase in the number of bits in the screen, by using a clock pulse of 5 MHZ in Test 6 instead of the 2.5 MHZ in Test 5 gave no overall significant reduction in error. Figure 6.10 shows the variation of error against duration in graphical form.

The tendency to make many type 2 errors at high disparity in the centre of the visual field decreases as duration increases. No significant variation of a type 1 errors in the range of durations tested was found. Increasing the number of bits on the screen (and hence providing more points for a correlation between the left and right eye visual fields) does not remove the tendency to make more type 2 than type 1 errors.

6.6. CONCLUSION

Tests 1 and 2 demonstrated that a monocular cue aids stereopsis. Because of this, the mode of presentation used in subsequent experiments involved the subject looking at a random dot pattern which, at the instant the stimulus was presented, changed to a new independent dot pattern. This changed back to the original, when the stimulus was removed. There was then no change in texture or illumination when the stimulus was presented and

no monocular cue to aid stereopsis.

The task of locating the depth of a small square in the centre of the visual field was found to be difficult at high binocular disparities. In this case there was a tendency for the subjects to judge a square that was actually behind the reference plane to appear in front. This effect did not disappear when the same experiment was repeated a week later nor was it affected by reducing the number of dots in the random dot pattern as in Test 5. It was, however, removed by increasing the duration of exposure to the stimulus.

FIG.6.1 RESULTS AND EXPERIMENTAL CONDITIONS FOR TEST 1

SIZE OF RECTANGULAR STIMULUS	$1.58^0 \times 1.1^0$
BINOCULAR DISPARITY	3 BITS AT 10MHZ, CONVERGENT (5.1')
EXPOSURE DURATION	2 TV FRAMES OR 80 MILLISECONDS
ILLUMINATION	1.4 LUMENS/SQ.FOOT (MEASURED AT VIEWING POLAROIDS)
SAMPLE SIZE	10 SUBJECTS, SEQUENCE LENGTH 4 TREATMENTS X 10 = 40

TABLE 6.1 RESULTS FOR THE FOUR MODES OF PRESENTATION

	TREATMENT 1	TREATMENT 2	TREATMENT 3	TREATMENT 4
Mean out of 10	9.9	5.0	5.6	7.2
$S_{\bar{X}}$ ✯	0.105	0.536	0.436	0.418
t	46.6*	0.	1.41	5.26*

TABLE 6.2 COMPARISON BETWEEN TREATMENT 1 AND TREATMENT 4

$\bar{X}_1 - \bar{X}_4$	2.7
$S_{\bar{X}_1 - \bar{X}_4}$	0.432
t	6.25*

* Significant at 5% level.

✯ $S_{\bar{X}}$ = standard deviation of the mean $\bar{X}$

FIG.6.2 RESULTS AND EXPERIMENTAL CONDITIONS FOR TEST 2

SAMPLE SIZE ..18 SUBJECTS, SEQUENCE LENGTH = 2 TREATMENTS x 20 = 40

SIZE OF SQUARE STIMULUS ..... $1.6^0 \times 1.6^0$

DURATION OF STIMULUS..... 1 TV FRAME OR 40 MILLISECONDS

ALL OTHER CONDITIONS AS FOR TEST 1

TABLE 6.3 AVERAGE SCORES (MEAN OF 18 SUBJECTS)

	NUMBER CORRECT	SQUARE REP. AS BLANK	BLANK REP. AS SQUARE	TOTAL NUM. OF SAMPLES
TREATMENT 1	15.22	3.89	0.89	20
TREATMENT 2	11.95	3.78	4.27	20

TABLE 6.4 SIGNIFICANCE OF NUMBER CORRECT

	MEAN $\bar{X}$	$S_{\bar{x}}$	t
TREATMENT 1	15.22	1.072	4.86*
TREATMENT 2	11.95	0.674	2.94*

TABLE 6.5 COMPARISON OF TOTAL PERFORMANCE FOR THE TWO TREATMENTS

	MEAN SQUARE	DEGREES OF FREEDOM	F
TREATMENTS	109.	1	7.56*
WITHIN TREATMENTS	14.4	34	

TABLE 6.6 COMPARISON OF THE ERRORS FOR EACH TREATMENT

	SQUARE REP. AS BLANK	BLANK REP. AS SQUARE	M_{ST} 1df	M_{WT} 34df	F
TREATMENT 1	3.89	0.89	92.2	8.48	10.9*
TREATMENT 2	3.78	4.27	1.84	6.25	0.294

TABLE 6.7 COMPARISON OF THE TREATMENTS FOR EACH ERROR

	TREATMENT 1	TREATMENT 2	M_{ST} 1df	M_{WT} 34df	F
SQUARE REP. AS BLANK	3.89	3.78	0.109	12.	0.0092
BLANK REP. AS SQUARE	0.89	4.27	115.	2.72	42.2*

TREATMENT 1 ...NO CHANGE IN RANDOM DOT PATTERN

TREATMENT 2 ...RANDOM DOT PATTERN CHANGES TO A SECOND INDEPENDENT PATTERN

* Significance level at 5%.

FIG.6.3 RESULTS OF EXPERIMENT 3

TABLE 6.8 ANALYSIS OF VARIANCE

	ERROR 1 "NEARER" REPORTED AS "FURTHER"						ERROR 2 "FURTHER" REPORTED AS "NEARER"						
DISPARITY	1	2	3	4	5	6	1	2	3	4	5	6	
$\bar{X}_k$	1.1	.85	.7	1.15	1.2	.7	.95	1.1	2.	3.	4.5	4.9	
S_k^2	1.88	.98	.75	1.42	1.43	.96	1.21	1.57	3.53	4.16	2.58	3.25	
$\bar{\bar{X}}$	0.95						2.74						d.f.
M_{ST}	1.04						57.1						5
M_{WT}	1.23						2.71						114
F	0.84						21.0*						

*Significance level 5%

TABLE 6.9 DUNCAN'S MULTIPLE RANGE TEST FOR ERROR 2

α = 0.01

PROTECTION LEVEL 95%

DISPARITY		DISPARITY 1	2	3	4	5	6	SHORTEST SIGNIFICANT RANGES
		0.95	1.1	2.0	3.0	4.5	4.9	
1	0.95		0.15	1.05	2.05	3.55	3.95	R_2 = 1.36
2	1.1			0.9	1.9	3.4	3.8	R_3 = 1.42
3	2.0				1.0	2.5	2.9	R_4 = 1.46
4	3.0					1.5	1.9	R_5 = 1.49
5	4.5						0.4	R_6 = 1.51
		1	2	3	4	5	6	

FIG. 6.4 RESULTS OF EXPERIMENT 4

TABLE 6.10 ANALYSIS OF VARIANCE

	ERROR 1 "NEARER" REPORTED AS "FURTHER"						ERROR 2 "FURTHER" REPORTED AS "NEARER"						
DISPARITY	1	2	3	4	5	6	1	2	3	4	5	6	
$\bar{X}_k$	1.6	.75	.75	1.	1.	1.3	.55	1.6	2.25	3.55	4.4	3.9	
S_k^2	1.94	.93	.72	1.79	1.26	2.12	1.08	2.04	2.09	2.47	2.56	4.09	
$\bar{\bar{X}}$	1.06						2.73						df
M_{ST}	2.53						41.52						5
M_{WT}	1.46						2.39						114
F	1.73						17.37*						

*Significance level 5%

TABLE 6.11 DUNCAN'S MULTIPLE RANGE TEST FOR ERROR 2

$\alpha = 0.01$

PROTECTION LEVEL 95%

DISPARITY		DISPARITY 1	2	3	4	6	5	SHORTEST SIGNIFICANT RANGES
		0.55	1.6	2.25	3.55	3.9	4.4	
1	0.55		1.05	1.7	3.0	3.35	3.85	$R_2 = 1.28$
2	1.6			0.65	1.95	2.3	2.8	$R_3 = 1.33$
3	2.25				1.3	1.65	2.15	$R_4 = 1.37$
4	3.55					0.35	0.85	$R_5 = 1.40$
6	3.9						0.5	$R_6 = 1.42$
		1	2	3	4	6	5	

FIG.6.5 EXPERIMENTAL CONDITIONS FOR TESTS 3 AND 4 AND A COMPARISON OF THEIR RESULTS.

NUMBER OF SUBJECTS 20

SEQUENCE LENGTH.....6 TREATMENTS x 2 LOCATIONS x 7 SAMPLES = 84

BINOCULAR DISPARITY....3.4'-20.4' IN 6 EQUAL STEPS(1-6 BITS AT 5MHZ)

DURATION OF STIMULUS.....2 TV FRAMES OR 80 MILLISECONDS.

ILLUMINATION.....1.4 LUMENS/SQ.FOOT (MEASURED AT VIEWING POLAROIDS)

SIZE OF SQUARE..... 1.58° x 1.58° (IN CENTRE OF VISUAL FIELD)

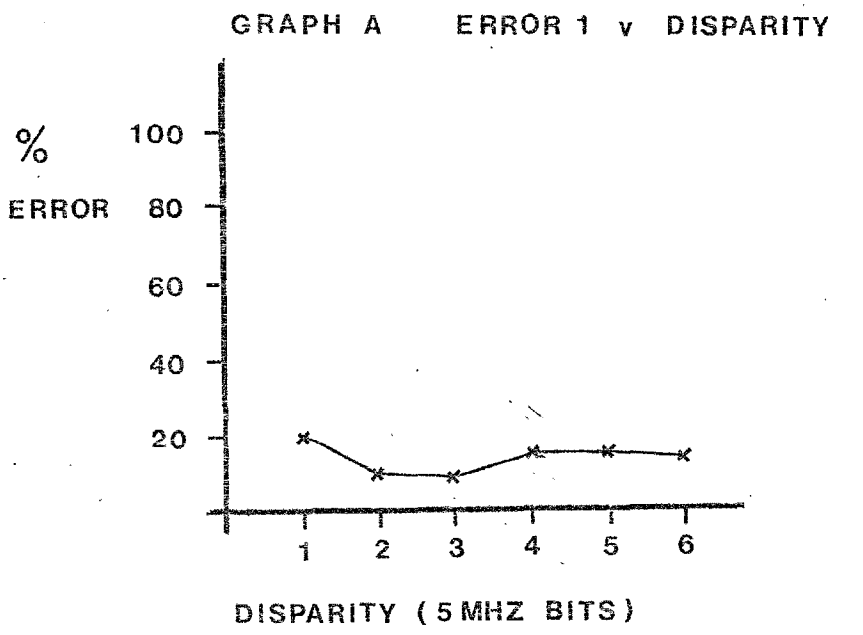
TABLE 6.12 A COMPARISON OF ERROR BIAS FOR TESTS 3&4(BIAS DETERMINED BY t TEST AT 5% SIGNIFICANCE LEVEL)

DISPARITY	TEST 3	TEST 4
1	insignificant difference	Error 1 > Error 2
2	insignificant difference	Error 1 > Error 2
3	Error 2 > Error 1	Error 2 > Error 1
4	Error 2 > Error 1	Error 2 > Error 1
5	Error 2 > Error 1	Error 2 > Error 1
6	Error 2 > Error 1	Error 2 > Error 1

TABLE 6.13 COMPARISON OF SCORES FOR TESTS 3&4 BY ANALYSIS OF VARIANCE (FACTOR A IS A TWO LEVEL FACTOR REPRESENTING TEST 3 AND TEST 4)

OBJECT OF COMPARISON	IDENTIFICATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F
TOTAL ERROR	A	0.3	1	0.3	0.154
	WITHIN TREATMENT	889.63	456	1.95	
ERROR 1	A	0.816	1	0.816	0.606
	WITHIN TREATMENT	307.43	228	1.345	
ERROR 2	A	0.0167	1	0.0167	0.0065
	WITHIN TREATMENT	582.2	228	2.55	

FIG.6.6 COMBINED RESULTS FOR EXPERIMENTS 3 AND 4



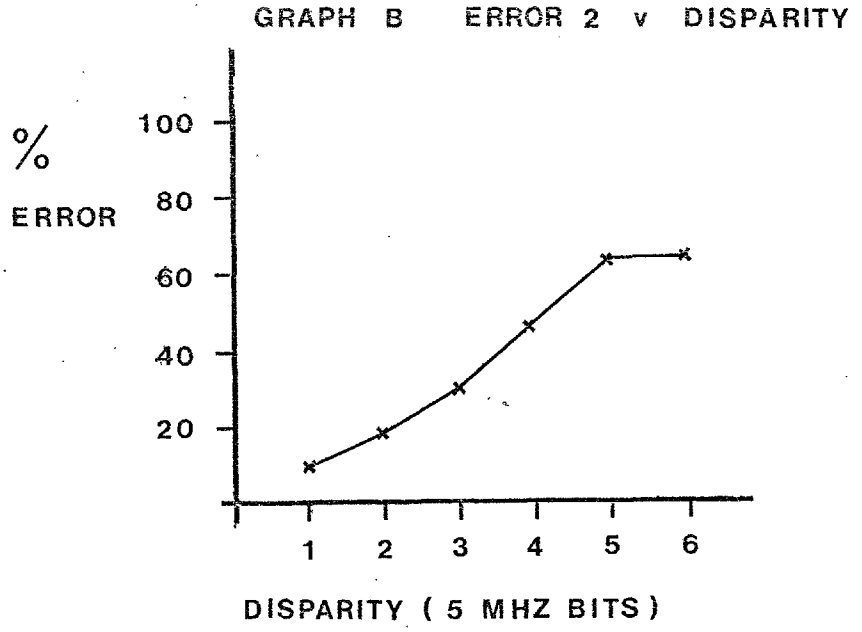


FIG.6.7 RESULTS OF EXPERIMENT 5

TABLE 6.14 ANALYSIS OF VARIANCE

ERROR 1 "NEARER" REPORTED AS "FURTHER"							ERROR 2 "FURTHER" REPORTED AS "NEARER"						
DURATION OF STIMULUS	2	3	4	5	6	7	2	3	4	5	6	7	
$\bar{X}_k$	1.55	1.40	1.2	1.3	.95	1.4	3.	2.9	2.	1.9	.95	.55	
S_k^2	2.89	1.52	2.17	2.96	1.63	3.31	3.68	3.78	1.79	3.15	1.31	.79	
$\bar{\bar{X}}$	1.3						1.88						df
M_{ST}	0.86						19.77						5
M_{WT}	2.41						2.42						114
F	0.357						8.16*						

*Significance level 5%

TABLE 6.15 DUNCAN'S MULTIPLE RANGE TEST FOR ERROR 2

$\alpha = 0.01$

		DURATION IN TV FRAMES						PROTECTION LEVEL 95%
		7	6	5	4	3	2	SHORTEST
DURATION		0.55	0.95	1.90	2.0	2.9	3.0	SIGNIFICANT RANGES
7	0.55		0.40	1.35	1.45	2.35	2.45	R_2=1.29
6	0.95			0.95	1.05	1.95	2.05	R_3=1.34
5	1.90				0.1	1.0	1.1	R_4=1.38
4	2.0					0.9	1.0	R_5=1.40
3	2.9						0.1	R_6=1.45
		7	6	5	4	3	2	

FIG.6.8 RESULTS OF EXPERIMENT 6

TABLE 6.16 ANALYSIS OF VARIANCE

	ERROR 1 "NEARER"REPORTED AS"FURTHER"						ERROR 2 "FURTHER"REPORTED AS"NEARER"						
DURATION OF STIMULUS	2	3	4	5	6	7	2	3	4	5	6	7	
$\bar{X}_k$	1.75	.75	.6	.7	.85	1.1	3.25	2.75	2.15	1.5	.9	.85	
S_k^2	2.62	1.78	.67	.85	1.61	2.41	5.25	3.36	2.34	3.21	1.04	.98	
$\bar{\bar{X}}$	0.958						1.9						df
M_{ST}	3.588						19.48						5
M_{WT}	1.81						2.7						114
F	1.98						7.21*						

*Significant at 5% level

TABLE 6.17 DUNCAN'S MULTIPLE RANGE TEST FOR ERROR 2

$\alpha = 0.01$

DURATION		DURATION IN TV FRAMES 7	6	5	4	3	2	PROTECTION LEVEL 95% SHORTEST SIGNIFICANT RANGES
		0.85	0.9	1.5	2.15	2.75	3.25	
7	0.85		0.05	0.65	1.30	1.90	2.40	$R_2 = 1.31$
6	0.90			0.60	1.25	1.85	2.35	$R_3 = 1.36$
5	1.5				0.65	1.25	1.75	$R_4 = 1.40$
4	2.15					0.60	1.1	$R_5 = 1.43$
5	2.75						0.50	$R_6 = 1.47$
		7	6	5	4	3	2	

FIG.6.9 EXPERIMENTAL CONDITIONS FOR TESTS 5 AND 6 AND A COMPARISON OF THEIR RESULTS

BINOCULAR DISPARITY ..... 20.4'(6 BITS AT 5 MHZ OR 3 BITS AT 2.5MHZ)

DURATION OF STIMULUS ..... 2-7 TV FRAMES IN 6 EQUAL STEPS(80-280MILLISECS)

SYSTEM CLOCK PULSE.....2.5MHZ(TEST 5),5MHZ(TEST 6)

ILLUMINATION,NUMBER OF SUBJECTS,SEQUENCE LENGTH,STIMULUS SIZE AND POSITION AS FOR TESTS 3&4 (FIG.6.5)

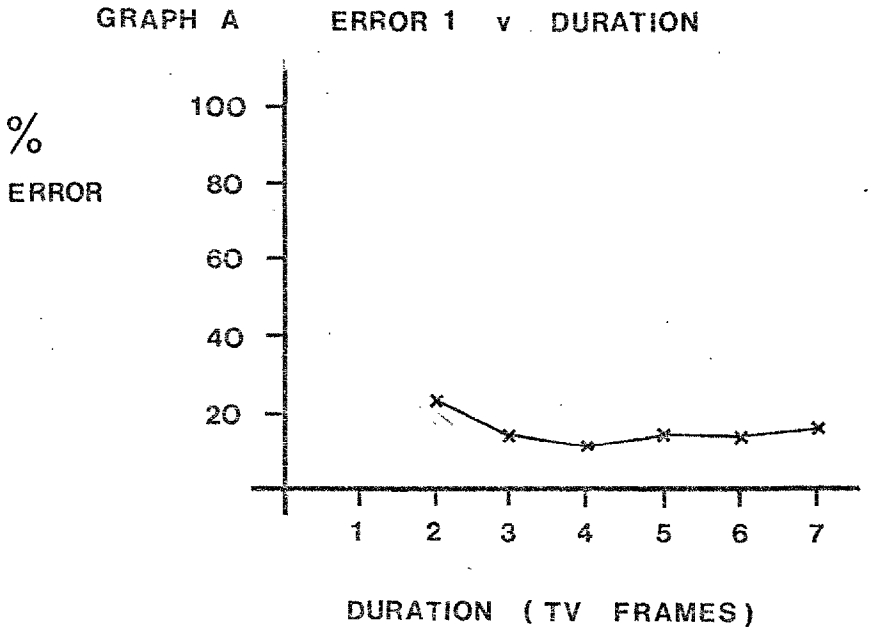
TABLE 6.18 A COMPARISON OF ERROR BIAS FOR TESTS 5&6 (BIAS DETERMINED BY t TEST AT 5% SIGNIFICANCE LEVEL)

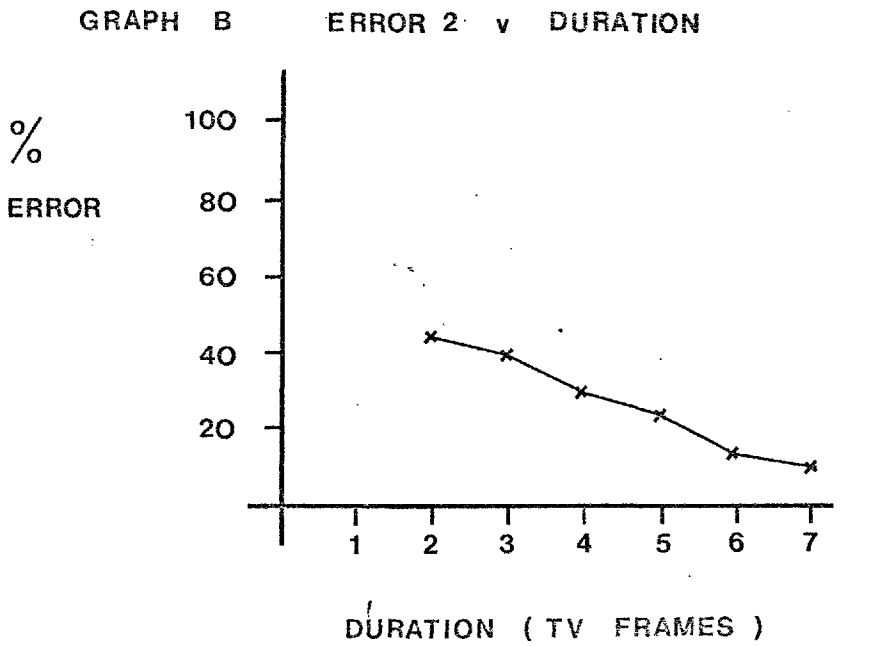
DURATION IN TV FRAMES	TEST 5	TEST 6
2	ERROR 2 > ERROR 1	ERROR 2 > ERROR 1
3	ERROR 2 > ERROR 1	ERROR 2 > ERROR 1
4	ERROR 2 > ERROR 1	ERROR 2 > ERROR 1
5	insignificant difference	ERROR 2 > ERROR 1
6	insignificant difference	insignificant difference
7	ERROR 1 > ERROR 2	insignificant difference

TABLE 6.19 COMPARISON OF SCORES FOR TESTS 5&6 BY ANALYSIS OF VARIANCE (FACTOR A IS A TWO LEVEL FACTOR REPRESENTING TEST 5 AND TEST 6)

OBJECT OF COMPARISON	IDENTIFI-CATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F
TOTAL	A	1.581	1	1.581	0.69
ERROR	WITHIN TREATMENT	1046.6	456	2.30	
ERROR 1	A	7.	1	7.	3.45
	WITHIN TREATMENT	463.75	228	2.03	
ERROR 2	A	0.0167	1	0.0167	0.0065
	WITHIN TREATMENT	582.9	228	2.56	

FIG.6.10 COMBINED RESULTS FOR EXPERIMENTS 5 AND 6





CHAPTER 7

EXPERIMENTS 7 - 11.

7.1. INTRODUCTION.

In chapter 6 stereopsis was studied as binocular disparity and duration of exposure were varied. In the experiment described in this chapter disparity and duration are held constant but position, shape and size of the stimulus are varied to provide more information for a model of stereopsis. The binocular disparity is set at six units with a clock-pulse of 5 MHZ which is an angular disparity of 20.4'. The stereoscopic stimulus is presented in the same way as in Experiments 3 - 6 and for a duration of two television frames or eighty milliseconds.

Ordinary monocular visual acuity varies with position of the stimulus in the visual field, acuity being highest in the centre of vision and falling off steadily as the peripheral angle increases. Likewise stereo-acuity varies with peripheral angle (BLAKEMORE, 1970). With spatial localisation there is an asymmetry between the two halves of the visual field, stereopsis taking place in the right cerebral hemisphere (referring to objects in the left half of the visual field) being more efficient than that localised in the left hemispere (DURNFORD & KIMURA, 1971). The extent of the region of single vision (Panum's fusional area) also varies with peripheral angle (OGLE, 1962) though is apparently symmetrical about the fixation point. Limitations of the equipment prevent small stimuli being presented to the subject at a peripheral angle of more than 3^{o} with the fixation point in the centre of the dot pattern though this angle may be doubled if the fixation point is moved to one edge of the picture. However, a peripheral angle of only 3^{o} is sufficient to ensure that the stimulus is represented in only

one cerebral hemisphere (BLAKEMORE, 1969).

The difficulty of forming a depth judgment of a small square in a random dot stereogram presented for a short time at a large binocular disparity has been demonstrated by Experiment 3.
The purpose of experiments 7 - 9 was to test the hypothesis that a small shift of position of this small square into the periphery would make the problem of depth localisation easier. If there are more disparity specific binocular units in the visual cortex tuned to a high disparity of 20' of arc for a stimulus positioned in the periphery than for a stimulus positioned in the centre of the visual field this could well be so. Alternatively problems associated with the naso-temporal division could make perception of stimuli at high binocular disparity more difficult in the centre of vision than in the periphery. Stereopsis is not possible for an object located far in front of the point of fixation unless there is intercerebral communication (see 2.4). In either case some improvement might be expected by moving the large-disparity-stereo-stimulus a little into the periphery although because of the asymmetry of function in the cerebral hemispheres it may be that a shift off centre in one direction only will cause an improvement.

In experiment 10 two rectangles of identical size were presented to the subjects (one at a time) as stimuli. One rectangle had its longest side vertical, the other its longest side horizontal. The centre of both rectangles was at the fixation point. This experiment was used to confirm the results of experiments 7-9 in that the two stimuli differed by virtue of one rectangle having more of its area in the periphery than the other. (i.e. the second movement of the horizontally-aligned rectangle about a vertical axis through the fixation point was greater than that of the vertically aligned rectangle).

Finally Experiment 11 tested the effect of a size increase. The stimuli were both square and centred at the fixation point with the larger having a side three times the length of the smaller. The smaller square was the one used in Experiments 3 - 6.

7.2. EXPERIMENTS 7, 8, 9.

In Experiment 7 the subject was asked to determine the depth (nearer or further than the fixation point and the reference plane) as it appeared for eighty milliseconds in one of seven positions chosen at random. The seven positions for the square included one in the centre of the visual field and three symmetrically located on either side to a maximum peripheral angle of 3^{o}. In all other respects the experiment was similar to the Experiments 3 - 6 repeated in chapter 6. Each subject received a sequence of a hundred samples whose order was independent of that given to all the other subjects and the answers to the first sixteen samples were discarded. The remaining eighty-four samples were equally distributed among the seven treatments and for each treatment the square was six times further from the subject than the fixation point and for six times it was nearer. Twenty subjects were used. The seven positions for the square and other experimental conditions are listed in Fig.7.2.

To say that the stereoscopic stimulus is a square is to say that the vertical and horizontal dimensions are identical but as has been already discussed (section 3.1) there is a perceptual uncertainty on the horizontal dimension. In addition it may appear greater when the square is located behind the fixation point than when it is in front.For the purposes of these experiments the horizontal dimension is taken to include half the ambiguous area of dots and the centre of the square, from which point peripheral angle is measured, is located accordingly.

The square area that was used as the stereoscopic stimulus was defined internally in the system (section 4.6) and its horizontal position was varied during the test by the experimenter so that the square lay in one of the seven positions. The experimenter was provided with his own monitor which displayed the random dot pattern with the stimulus area blanked out irrespective of whether the stimulus was being presented to the subject or not. Superimposed on the monitor was a grid centred on the fixation point to locate the seven positions. The experimenter was thus able to move the square to its required position whilst the subject was waiting for the next sample.

After the test many subjects inquired as to whether the exposure duration was also varied as well as the position. A check on the timing system confirmed that it was working properly. It was assumed that the varying difficulty of perceiving the stimulus as its position was varied induced the response on the part of the subjects that the duration also varied.

The results of experiment 7 are tabulated in Table 7.1 on Fig.7.1. For both types of error (nearer appearing further and further appearing nearer) a significant F ratio is obtained in the analysis of variance. Duncan multiple range tests were performed (Tables 7.2 and 7.3) for both types of error. A graphical representation of the results is shown in Fig.7.3. A & B .

Graph B shows the hemispherical asymmetry of the brain in spatial location tasks which has been noted before (DURNFORD & KIMURA, 1971). Actually, Experiment 7 and the above-cited work differ in several ways. In Durnford's original experiment, only the fixation point was visible before the stimulus appeared and during the presentation the entire random dot pattern fell on one half of the visual field. The task for the subject

was to discriminate between several different shapes that appeared in front of the reference plane at some relative convergent disparity. Since the various shapes were defined only by binocular disparity, and since binocular disparity is a primary cue for spatial localisation, it could be concluded that differences in task performance for the left and the right visual fields were evidence for hemispherical asymmetry in the general ability to locate objects in space. However, if the cerebral hemispheres were equally able to group dots of equal disparity together but showed different ability in recognising the form or shape of these equal-disparity areas the same experimental result would be obtained. It is more reasonable to keep the shape of the stereoscopic stimulus constant and to ask the subject to recognise variations in disparity. In Experiment 7 the task is to discriminate between convergent and divergent disparity of equal magnitude.

In Table 7.5 the results for positions 1 and 7 the two extreme positions at a peripheral angle of 3^{o} are compared. There is no significant difference between the error 1 scores but for error 2 (further appearing nearer) position 7 in the right visual field has a significantly higher value position 1 in the left visual field.

For the left half of the visual field (analysed in the right cerebral hemisphere which is thought to be better than the left for spatial location tasks) graphs A & B in Fig.7.3 show a pattern familiar to Experiments 3 - 6. The error type 2 is highest at position 4 in the centre of the visual field and decreases as the square moves towards the periphery. The type 1 error is lower on average but increases for those treatments where the type 2 error is low. Table 7.4 in Fig. 7.2 shows the significant error preferences in the seven treatments and incidentally displays another aspect of hemispherical asymmetry. Type 2 errors are made more often than type 1 errors in

the centre of the visual field and at a peripheral angle of 1^{o} in either direction. There is no bias at angles of 2^{o} and 3^{o} in the right visual field and at 2^{o} in the left visual field but the bias is inverted on the extreme left side in position 1.

Taking these results as they stand one might make the following statement. Random dot stereograms containing a small square at high relative divergent disparity to the reference plane shown briefly in the centre of the visual field to a subject are frequently confused with similarly presented stimuli of convergent disparity of equal magnitude. There is then a definite tendency on the subject's part to place such stimuli nearer to him than the reference plane rather than further away. This effect disappears as the stimulus is presented at a peripheral angle of 2^{o} or 3^{o}.

The explanation for the inverted bias at position 1 is that the subject feels a need to record an approximately equal number of squares as nearer to him than the fixation point as further away. If for one treatment he records a majority as nearer to him then he will make up for this in other treatments where the effect is not present. If the subject could not see the square very clearly when it was presented to him in the periphery than he might have a tendency to guess in a certain way to compensate for the answers he was recording in the centre of the visual field where he could always see the square. To investigate this possibility Experiment 8 was conducted.

The hypothesis to be tested in Experiment 8 was that when the subject found it difficult to see the square he recorded that it was further from him than the reference plane. To do this a similar experiment to Experiment 7 was designed but without the subject being informed several of the samples contained no square at all. If without any evidence to position

the subjects showed a tendency to record that the square was further away then the hypothesis is proved. "No square at all" in a random dot stereogram is equivalent to a square at zero disparity and so the experiment could be looked upon as testing the bias to either convergent or divergent disparity when zero disparity is presented.

The same sequence of length of a hundred samples with the first sixteen being discarded was used. However, there were in Experiment 8 only five positions for the square stimulus. As before, one was in the centre of the visual field but only two were placed symmetrically on either side of the fixation point. These were at 3^{o} and at $1\frac{1}{2}^{o}$. The twenty-four samples that were, in Experiment 7, used for the other two treatments were used in Experiment 8 as blanks (stimuli with zero binocular disparity). Fourteen subjects were engaged in this experiment.

After the experiment, no subject remarked on the blank stimuli. It was therefore assumed that in all cases stereopsis in at least one of the five positions was not very definite. Table 7.6 in Fig.7.5 gives an analysis of the subject's location of these zero disparity stimuli. A significant difference exists between the scores for the two locations and in fact subjects placed three times as many of the blanks behind the fixation point of in front. This proves the hypothesis.

It is clear that before conclusions can be drawn from an experiment like Experiment 7 some more knowledge of the subject's stereoscopic vision over the region of the visual field of interest must be known. Experiment 9 was conducted to select,if possible,a group of subjects who could identify positively squares presented in at least one half of the visual field under the conditions of Experiment 8.

A sequence of a hundred samples, of which the first ten were discarded, were presented to each subject. Of the remaining ninety, forty-five

were blanks and the other forty-five were divided equally among the five positions of Experiment 8 (Fig.7.5). All squares were located in front of the reference plane. The subjects were told where the stimulus could appear and also that it might not appear at all. They were asked to record the position of the square if it appeared (one out of five possibilities) or to record its absence if it did not appear. They were not informed of the frequency of any of the six types of sample. All other experimental conditions were as for Experiment 8. Twenty subjects were screened in this way.

The conditions for "passing" this test were as follows. The subject was allowed only one error out of the twenty-seven samples that referred to positions (Fig.7.5) 1, 2 and 3 or 3, 4 and 5. That is he must correctly locate the square that fell in the centre and at least one half of the visual field. Secondly, not more than 10 % of the blanks (i.e. 4) could be incorrectly placed on the side on which the subject had apparently better stereopsis.

Under these conditions five passed the test of which subjects perceived more correctly in the left visual field and one in the right. One subject apparently perceived equally well in both halves of the visual field. All five of these subjects were included in the fourteen that did Experiment 8 and their results for this experiment are shown in Table 7.7, Fig.7.4.

In contrast to the results of Experiment 7 a significant F ratio in the analusis of variance is found only for the type 2 error. The Duncan Multiple range test for this error is shown in Table 7.8. The three treatments in these tables refer to the centre of the visual field (1), a peripheral angle of $1\frac{1}{2}^{o}$ (2) and a peripheral angle of 3^{o} (3). The results are displayed graphically in graphs C, D in Fig.7.3. Table 7.9, Fig.7.4, demon-

strates that a significant bias for type 2 errors exists only in the centre of the visual field. The effect disappears in the periphery.

Although it is not very satisfactory to draw conclusions from so few subjects it is clear that the conclusions from Experiment 7 are substantiated by a special group of subjects who possessed very good stereopsis in at least one half of the visual field. The possible criticism of Experiment 7, namely that subjects did not see the stimulus very well when it was presented off-centre and recorded an answer which depended more on their answers for the stimulus in the centre of the visual field, which they could see very well, than on the evidence presented to them in the previous sample, is then overruled.

7.3. EXPERIMENTS 10 and 11.

In Experiment 7, 8, 9, one difference between the square in the centre of the visual field and that slightly in the periphery was that the fixation point covered a small area where the square appeared. The possible effect of the fixation point, which was a small black cross, on the results was minimised by removing it when the stimulus was presented. The fixation point is absolutely necessary to direct a visual signal to some particular part of the retina but it is undesirable that it should affect the experiment in any other way. One rectangle was used and was aligned either horizontally or vertically as mentioned in section 7.1 and shown in Fig.7.6 where other experimental details are listed. The fixation point covered the same area of both stimulus 1 and 2 and so cannot by itself be a factor in any differences between the perception of the two stimuli.

The rectangles were presented randomly as was their depth relative to the reference plane. The subjects, who were eighteen in number, were not asked to discriminate between the two stimuli but only to record their

depth as either being closer or further from them than the point of fixation.

In order to get a rapid changeover from one stimulus to another the horizontally aligned rectangle was generated electronically within the system whilst the vertical rectangle was presented via a transparency to a TV.camera. The experimenter then only had to switch in one of these signals to present the stimulus.

The results are shown in Tables 7.10, 11, and 12. A significant difference between the two types of error existed only for the vertical rectangle where the subjects made significantly more type 2 errors than type 1 errors. There was no significant difference in the scores for type 1 errors between the two stimuli but more type 2 errors were made for stimulus 1 than for stimulus 2.

Therefore the differences in response between the vertical and horizontal rectangle centrally placed in the visual field are similar to the differences in response between the square centrally located and the square located in the periphery as in Experiments 7 and 8. In the latter case the square stimuli were of identical size but had different first and second moments about a vertical axis through the point of fixation. In Experiment 10 the two stimuli differed only in the second moment about this axis.

In Experiment 11 a size increase was investigated. The smaller square stimulus was the same size as that as used for Experiments 3 - 6. The experimental conditions are listed in Fig.7.7. The experimental design and the task given to the subjects were identical to Experiment 10 but two more subjects, making a total of twenty were used. The results are shown in Tables 7.13, 14 and 15, Fig.7.7.

An increase in size at this high binocular disparity of 20.4' causes

a decrease in both types of error. The familiar error bias of more type 2 errors being made than type 1 errors is elicited only by the small square.

It is reasonable that an increase in size yielding more evidence of the binocular disparity of a group of dots should result in better perception.

7.4. CONCLUSIONS.

Two types of asymmetry in the visual field have been encountered in the reported experiments. Firstly the left/right asymmetry due to the differential abilities in spatial localisation of the two cerebral hemispheres was noted in Experiment 7. Secondly in Experiment 10 a rectangle when aligned horizontally and presented briefly at high binocular disparity was more easily located in depth than the same rectangle aligned vertically. In both alignments the centre of the rectangle was at the point of fixation so that an equal area lay in each half of the visual field. If, as suggested by Blakemore (BLAKEMORE, 1970) a central strip of retina exists that is represented in both hemispheres, it might be supposed that, with hemispherical preference in stereopsis as confirmed by Experiment 7, the vertical rectangle being completely represented in the right hemisphere would be perceived more readily than the horizontal rectangle of which only a fraction is thus represented. But the results show the reverse.

The difficulties in stereopsis, that were noted in chapter 6, for a small square at high divergent binocular disparity presented briefly in a random dot stereogram have been shown to exist only in the centre of the visual field. This result, indicated by Experiment 7, was thought doubtful because of the possibility of subjects guessing for squares shown in the periphery which might not have been seen very clearly in order to

compensate for the bias in the centre of the visual field. This possibility was largely reinforced by Experiment 8 but by specially selecting a smaller group of subjects who could see well on at least one side of the fixation point the result indicated by Experiment 7 was confirmed. It is clear from the results of this small group of subjects how much more certain stereopsis with large disparities is at 3^{o} in the periphery than in the centre of the visual field.

Finally, Experiment 11 in which a size increase is investigated, adds nothing to the argument. It may be noted, however, that increasing the size of the stimulus gives an overall increase in correct depth judgements and that no bias exists in the small numbers of errors made.

FIG.7.1 RESULTS OF EXPERIMENT 7

TABLE 7.1 ANALYSIS OF VARIANCE

	ERROR 1 "NEARER" REPORTED AS "FURTHER"							ERROR 2 "FURTHER" REPORTED AS "NEARER"							
POSITION (SeeFig7.2)	1	2	3	4	5	6	7	1	2	3	4	5	6	7	
$\bar{X}_k$	2.55	2.25	1.05	1.1	1.3	1.25	2.3	1.35	2.55	3.3	3.65	2.95	2.3	2.55	
S_k^2	3.1	2.09	2.16	2.2	1.59	1.57	3.48	1.92	2.47	7.17	7.5	2.05	2.85	3.1	
$\bar{\bar{X}}$	1.69							2.66							df
M_{ST}	8.43							11.13							6
M_{WT}	2.31							3.86							133
F	3.65*							2.88*							

*Significant at 5% level

TABLE 7.2 DUNCAN'S MULTIPLE RANGE TEST FOR ERROR 1

	POSITION	3	4	6	5	2	7	1	$\alpha = 0.01$ PROTECTION LEVEL=95% SHORTEST SIGNIFICANT RANGES
POSITION		1.05	1.10	1.25	1.30	2.25	2.30	2.55	
3	1.05		0.05	0.2	0.25	1.2	1.25	1.5	$R_5 = 1.38$
4	1.1			0.15	0.20	1.15	1.2	1.45	$R_6 = 1.40$
6	1.25				0.05	1.0	1.05	1.30	$R_7 = 1.42$
		3	4	6	5	2	7	1	

TABLE 7.3 DUNCAN'S MULTIPLE RANGE TEST FOR ERROR 2

	POSITION	1	6	7	2	5	3	4	$\alpha = 0.01$ PROTECTION LEVEL=95% SHORTEST SIGNIFICANT RANGES
POSITION		1.35	2.3	2.55	2.55	2.95	3.30	3.65	
1	1.35		0.95	1.20	1.20	1.60	1.95	2.30	$R_5 = 1.77$
6	2.30			0.25	0.25	0.65	1.00	1.35	$R_6 = 1.80$
		1	6	7	2	5	3	4	$R_7 = 1.83$

FIG.7.2 EXPERIMENTAL CONDITIONS AND RESULTS FOR TEST 7

AREA OF DOT PATTERN..... $8^{\circ}x5.5^{\circ}$

SYSTEM CLOCK PULSE..... 5MHZ

DURATION OF STIMULUS..... 2 TV FRAMES(80 MILLISECONDS)

BINOCULAR DISPARITY..... 6 BITS AT 5 MHZ (20.4')

AREA OF SQUARE STIMULUS.....1.58° x 1.58°

ILLUMINATION.....1.4LUMENS/SQ.FOOT(MEASURED AT VIEWING POLAROIDS)

NUMBER OF SUBJECTS.....20

SEQUENCE LENGTH.....7 TREATMENTS x 2 LOCATIONS x 6 SAMPLES = 84

	LEFT VISUAL FIELD			CENTRE	RIGHT VISUAL FIELD		
POSITION	1	2	3	4	5	6	7
PERIPHERAL ANGLE	-3°	-2°	-1°	0°	$+1^{\circ}$	$+2^{\circ}$	$+3^{\circ}$

TABLE 7.4 VARIATION OF ERROR BIAS WITH POSITION IN THE VISUAL FIELD

(BIAS DETERMINED BY t TEST AT 5% SIGNIFICANCE LEVEL)

POSITION	ERROR BIAS
1	ERROR 1 > ERROR 2
2	insignificant diff.
3	ERROR 2 > ERROR 1
4	ERROR 2 > ERROR 1
5	ERROR 2 > ERROR 1
6	insignificant diff.
7	insignificant diff.

TABLE 7.5 COMPARISON OF SCORES FOR THE EXTREME LEFT AND RIGHT HAND POSITIONS

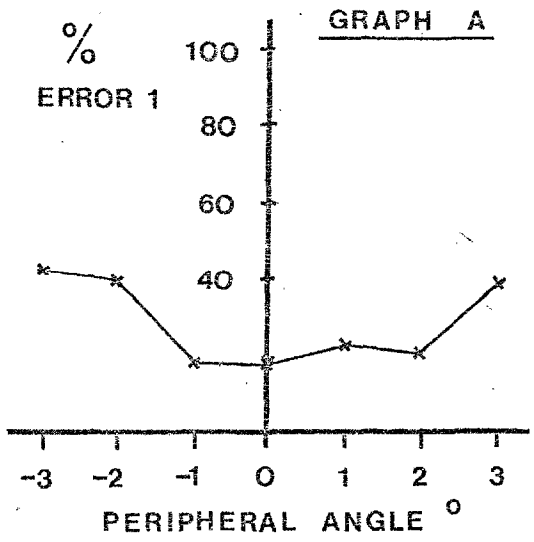
	ERROR 1		ERROR 2	
POSITION	MEAN	MEAN SQUARE	MEAN	MEAN SQUARE
1	2.55	3.10	1.35	1.92
7	2.30	3.48	2.55	3.10
$S_{\bar{X}_1-\bar{X}_2}$	0.574		0.448	
t	0.438		2.68*	

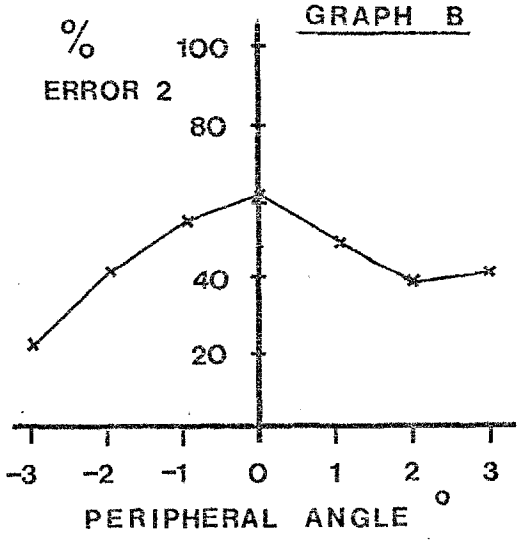
*Significant at at 5% level

FIG.7.3 RESULTS OF EXPERIMENT 7 AND 8

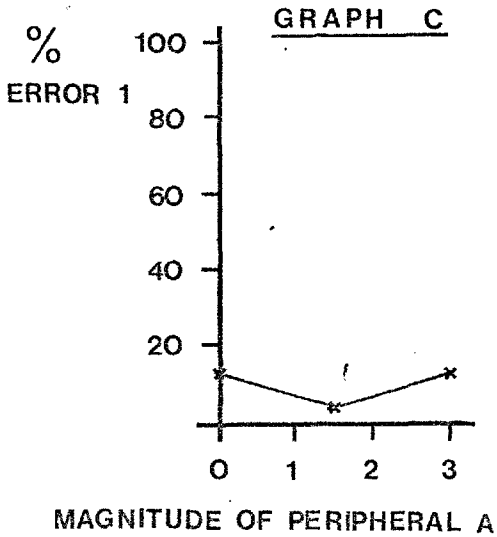
GRAPHS OF ERROR v PERIPHERAL ANGLE

EXPERIMENT 7





EXPERIMENT 8



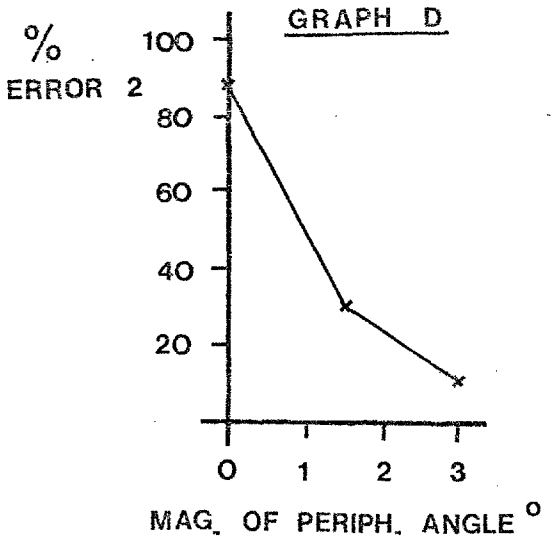


FIG 7.4 RESULTS OF EXPERIMENT 8(FROM THE FIVE SUBJECTS SELECTED BY EXPERIMENT 9)

TABLE 7.7 ANALYSIS OF VARIANCE

	ERROR 1 "NEARER"REPORTED AS"FURTHER"				ERROR 2 "FURTHER"REPORTED AS NEARER			
POSITION (See Fig.7.5)	1	2	3		1	2	3	
$\bar{X}_k$	0.8	0.4	0.8		5.2	1.8	0.6	
S_k^2	1.7	0.8	0.7		3.2	1.7	0.3	
$\bar{\bar{X}}$	0.67				2.53			df
M_{ST}	0.268				28.5			2
M_{WT}	1.07				1.73			12
F	0.25				16.5*			

*Significant at 5% level

TABLE 7.8 DUNCAN'S MULTIPLE RANGE TEST FOR ERROR 2

		POSITION 3	2	1	α = 0.01 PROTECTION LEVEL = 98% SHORTEST SIGNIFICANT RANGES
POSITION		0.6	1.8	5.2	
3	0.6		1.2	4.6	R_2 = 2.78
2	1.8			3.4	R_3 = 2.90
		3	2	1	

TABLE 7.9 VARIATION OF ERROR BIAS WITH POSITION IN THE VISUAL FIELD

POSITION	ERROR BIAS (By t test at 5% sig. level)
1	ERROR 2 > ERROR 1
2	insignificant difference
3	insignificant difference

FIG 7.5 EXPERIMENTAL CONDITIONS AND RESULTS OF EXPERIMENT 8

NUMBER OF SUBJECTS.....14

SEQUENCE LENGTH..... 5 POSITIONS x 2 LOCATIONS x 6 SAMPLES
+ 24 BLANKS = 84

	LEFT VISUAL FIELD		CENTRE	RIGHT VISUAL FIELD	
POSITION	1	2	3	4	5
PERIPHERAL ANGLE	-3°	-1.5°	0°	$+1.5^{\circ}$	$+3^{\circ}$

AREA OF DOT PATTERN, CLOCK PULSE, DURATION OF STIMULUS, BINOCULAR DISPARITY, AREA OF SQUARE STIMULUS AND ILLUMINATION AS FOR EXPERIMENT 7 (FIG 7.2)

TABLE 7.6 ANALYSIS OF LOCATION OF "BLANKS"

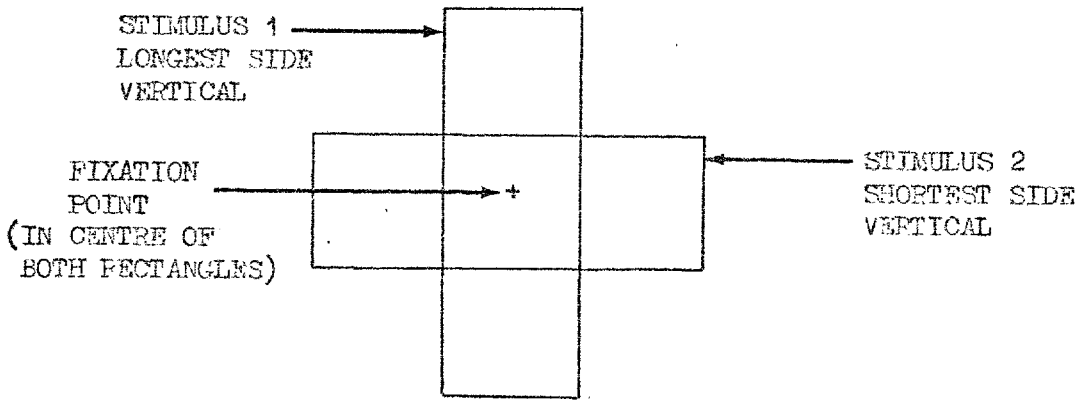
Mean (out of 24) placed "nearer"	5.93
Mean (out of 24) placed "further"	18.07
Standard deviation of mean	1.245
t (13 degrees of freedom)	4.87*

*Significant at 5% level

FIG 7.6 CONDITIONS AND RESULTS OF EXPERIMENT 10

NUMBER OF SUBJECTS.....18

SEQUENCE LENGTH..... 2 TREATMENTS x 2 LOCATIONS x 20 SAMPLES = 80



RATIO OF LONGEST SIDE TO SHORTEST SIDE 3:1

ANGLE SUBTENDED BY SHORTEST SIDE..... 1.58^{o}

AREA OF DOT PATTERN, CLOCK PULSE, DURATION OF STIMULUS, BINOCULAR DISPARITY, AND ILLUMINATION AS FOR EXPERIMENT 7 (FIG.7.2)

TABLE 7.10 RESULTS OF EXPERIMENT 10

	ERROR 1 "NEARER" REPORTED AS "FURTHER"		ERROR 2 "FURTHER" REPORTED AS "NEARER"	
	STIMULUS 1	STIMULUS 2	STIMULUS 1	STIMULUS 2
$\bar{x}_k$	5.94	4.22	8.89	3.78
s_k^2	12.17	9.12	14.52	11.59

TABLE 7.11 VARIATION OF ERROR BIAS WITH STIMULUS

STIMULUS	COMPARISON*
STIMULUS 1	ERROR 2 > ERROR 1
STIMULUS 2	insig. diff.

TABLE 7.12 COMPARISON OF THE TWO STIMULI FOR EACH ERROR

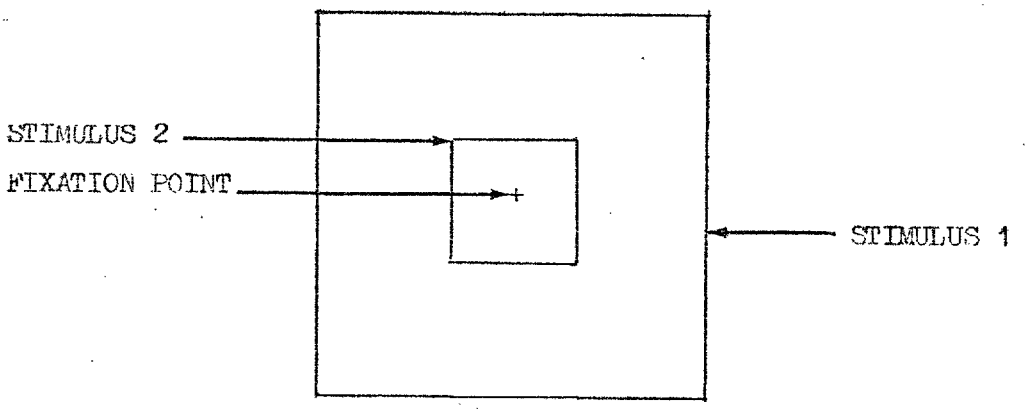
ERROR	COMPARISON*
ERROR 1	insig. diff.
ERROR 2	STIM. 1 > STIM. 2

* t test at 5% significance level

FIG 7.7 CONDITIONS AND RESULTS OF EXPERIMENT 11

NUMBER OF SUBJECTS 20

SEQUENCE LENGTH..... 2 TREATMENTS x 2 LOCATIONS x 20 SAMPLES = 80



DIMENSION OF SMALL SQUARE.....1.58° x 1.58°

DIMENSION OF LARGE SQUARE.....4.74° x 4.74°

AREA OF DOT PATTERN, CLOCK PULSE, DURATION OF STIMULUS, BINOCULAR DISPARITY, AND ILLUMINATION AS FOR EXPERIMENT 7 (FIG.7.2)

TABLE 7.13 RESULTS OF EXPERIMENT 11

	ERROR 1 "NEARER" REPORTED AS "FURTHER"		ERROR 2 "FURTHER" REPORTED AS "NEARER"	
	STIMULUS 1	STIMULUS 2	STIMULUS 1	STIMULUS 2
$\bar{x}_k$	1.25	6.3	1.55	11.55
s_k^2	4.93	21.17	2.89	24.79

TABLE 7.14 COMPARISON OF THE TWO STIMULI FOR EACH ERROR

ERROR	COMPARISON*
ERROR 1	STIM. 2 > STIM. 1
ERROR 2	STIM. 2 > STIM. 1

TABLE 7.15 VARIATION OF ERROR BIAS WITH STIMULUS

STIMULUS	COMPARISON*
STIMULUS 1	insignificant difference
STIMULUS 2	ERROR 2 > ERROR 1

*t test at 5% significance level

CHAPTER 8

EXPERIMENTS WITH INTEROCULAR DELAY.

8.1. INTRODUCTION

The work of Dodwell (DODWELL & ENGELS, 1963) and Efron (EFRON,1957) on the critical frequency of stereoscopic fusion has already been discussed in chapter 2. Both these workers postulated a system of stereoscopic fusion that contained inertia and performed experiments with interocular delay to investigate the dynamics of the system. Much earlier work (SHERRINGTON, 1906) indicated that the flicker fusion frequency (not the stereoscopic fusion frequency) could be reduced by binocular presentation of out of phase (temporal) stimuli. Although Sherrington's figure for the monocular initial flicker fusion frequency is much higher than what is now accepted as correct, the reduction in this figure by the binocular presentation of out-of-phase instead of in-phase stimuli has been verified (FOX & BLAKE, 1973) by other researchers.

The relationship between interocular delay and stereoscopic acuity has also been studied (WIST &GOGEL, 1966; OGLE, 1963). Wist and Gogel found that for interocular delays up to thirty-two milliseconds there was negligible deterioration in stereoscopic acuity. Ogle looked for a critical delay at which fall in stereoacuity would be significant and found that for repetitive stimulation with a flash dur ation of fifty milliseconds the critical delay was twenty-five milliseconds. In the same article Ogle reported a practical attempt in World War II to gain stereopsis from binocular stimulation with interocular delay. An observer in an aeroplane viewed the ground below with the line joining his two eyes parallel to the principle axis of the aircraft. Apertures to control the light to the

two eyes were opened alternately so that first one eye saw the ground below for a short time and then, after an interval, the second eye was briefly exposed. The interval allowed the aeroplane to change its position between exposures so that the effective interocular distance was increased and the relative depth of objects on the ground exaggerated. The desired stereoscopic effect was not produced because the aircraft did not travel fast enough for an effective interocular distance to be created before the occurrence of horizontal flicker (EFRON, 1957) caused by apparent motion between binocular disparate images temporally separated.

Interocular delay has also been studied in relation to the investigation of binocular summation of subthreshold stimuli. Under certain conditions (FOX & BLAKE, 1973) a stimulus which is not perceived when shown to one eye only may be perceived if shown to both. It has been further found (BATTERSBY & DEFABAUGH, 1969) that the threshold for detection of a five millisecond test stimulus presented to one eye was significantly decreased when paired with a successive five millisecond sub-threshold flash presented to the corresponding area of the other eye but that this decrease in threshold was limited to a flash interval of less than fifty milliseconds.

Other work on interocular delay reported in the literature has generally been centred around the illusion known as the Pulfrich pendulum which is described in section 8.3. This phenomenon is generally thought to be due to the relationship between retinal luminance and the delay between retinal stimulation and cortical reception of the corresponding neural signal. It has been shown (JULESZ & WHITE, 1969) that stereopsis may be restored to the perception of dynamic random dot stereograms presented with interocular delay by darkening the image shown to the "leading" eye. This experiment, which has been repeated by the author, demonstrates the importance of simultaneity over other fidelity criteria for stereopsis.

When a dynamic random dot stereogram designed to display a central square at a binocular disparity of about six minutes of arc is presented with an interocular delay of about forty milliseconds, each eye sees a well-defined and illuminated picture but stereopsis does not occur. Stereopsis is recovered by rotating another piece of polaroid in front of the "leading" eye to darken its picture. At the point of recovery simultaneity is restored to the point of binocular fusion in the visual cortex but one retinal image is much darker than the other (a fact that might be expected to lead to some binocular rivalry) and as a result is not so well defined. It would seem that these differences between the retinal images are much less important to their proper stereoscopic fusion than temporal separation between the nerve signals at the visual cortex.

In this chapter three experiments are described. The first is inspired from the results of the previous experiments described in chapters 6 and 7. It is designed to investigate the nature of the nasotemporal division in the retina and the subsequent double representation of a central strip of retina in each cerebral hemisphere. The second is an investigation of a Pulfrich phenomenon that occurs when dynamic random dot stereograms are presented to the observer with interocular delay. The results of this experiment suggested the possibility that the system of binocular fusion in the visual cortex may adapt itself to deal with interocular delay. Finally, an experiment is described which tested this hypothesis by examining the stimulus threshold necessary for perception when the stimulus is masked with noise binocularly presented with interocular delay.

8.2. EXPERIMENT 12

In this experiment stereoscopic stimuli are presented to subjects with a time lag between the left and right eye's stereoscopic component.

By presenting this time lag to each eye in turn any asymmetry of binocular fusion may be studied. As discussed in chapter 7 cerebral dominance gives rise to asymmetry of perception in the visual field but ocular dominance also exists and becomes important in situations where binocular rivalry occurs (CGLE, 1962). However, the possible correlation between eye dominance and interocular delay is not to be investigated in Experiment 12 but rather the asymmetry in the effect of interocular delay for a small stimulus at high binocular disparity in the centre of the visual field. Thus the aim of the experiment is to show that the perception of a small stimulus sagittally near the fixation point is equally degraded by equal delays put in the left or right eye's path but this is not so for the same stimulus sagitally further from the fixation point.

Objects in space that stimulate points in the nasal hemi-retina of one eye and the temporal hemi-retina of the other may be located in fusion points in one cerebral hemisphere only. If, however, an object stimulates two nasal or two temporal hemi-retinae then fusion can only take place if there is communication between the cerebral hemispheres. This is the function of the cerebral bridge or corpus collosum (BLAKEMORE, 1970). In the first case, when only one hemisphere is involved, the transmission times from the each eye to the point of binocular fusion will be roughly equal. In the second case when an extra neural pathway through the corpus collosum is likely to be involved these transmission times will be unequal. In neural communications the velocity of an impulse in a nerve fibre is finite but the chief sources of delay are at the "neural relay stations" where synaptic inputs are accepted and where their number over a period of time affect the frequency of the nerve impulses given at the output.

An object nearer to the observer than the fixation point and in the centre of the visual field is represented in a fused form in the right

cerebral hemisphere by nerve fibres diverted (through the L.G.N.) from the right eye's temporal hemi-retina and by nerve fibres from the left eye's temporal hemi-retina via the corpus collosum. The transmission time from the left eye to the point of binocular fusion in the right cerebral hemisphere is thus longer than the transmission time from the right eye. It will be better for fusion in the right-hemisphere if the right eye's picture has a time lag with respect to the left eye's picture than vice versa. As regards binocular fusion in the left hemisphere it is more desirable that the left eye's picture arrives after the right eye's.* For objects in the centre of the visual field, which are located further from the observer than the fixation point, all these relations are reversed so that after the neural crossover in the optic chiasm the right hemisphere receives nerve fibres from the left eye direct but fibres from the right eye via the corpus collosum.

Perception may vary according to which eye receives a delayed stimulus if one of the following are true. If the right cerebral hemisphere is more efficient in binocular fusion than the left it may be better to degrade the left hemispheres point of fusion more than the right hemisphere's than vice versa. Alternatively in the event of binocular representation in both hemispheres priority may be given to information in one. In this case it would be better that this point of fusion received binocular signals relatively less out of phase than the corresponding point in the other hemisphere. A third possibility is that projections from one hemisphere to the other are stronger than the reverse process. This might be also yield asymmetry with interocular delay.

There is the possibility that eye dominance can effect experiments with interocular delay. If this is the case it would be expected to affect the perception of square behind the fixation point in the same way as a

* Perception involves the combination of information from the fusion points in both hemispheres. Any asymmetry in the effect of interocular delay then depends upon how this combination is made or the relative strengths of the fusion points of the two hemispheres. This is discussed in the next paragraph.

square in front of the fixation point. There would also be no difference in the effect of interocular delay on stimuli of different binocular disparity in the centre of the visual field.

The method of presenting stereoscopic stimuli for brief periods with interocular delay has been described fully in chapter 4 but it will be summarised here. Whilst waiting for the warning buzzer the subject views binocularly a stationary dot pattern consisting of one plane. At the end of the buzzer one eye's picture changes to a dynamic picture for the required number of frames set by the timer and then reverts to the stationary dot pattern displayed initially. The other eye's picture goes through the same sequence but a time lag exists between the two. The dynamic noise patterns displayed yield, if the interocular delay is not too great, a small area at a different depth level to the reference plane when the two patterns are binocularly fused. There is no monocular cue to stereoscopic depth but there does exist a cue to the direction of interocular delay although with a delay of about ten milliseconds as used in Experiment 12 it is unlikely that this could be used. As described in chapter 4 the system used to produce interocular delay involves a phase difference in the vertical scanning of the two TV monitors. Thus, even when a stationary pictures is displayed an interocular delay exists unless the set delay is an integral number of frames. This delay is not apparent to the observer.

The samples are presented to the subjects with interocular delay varying randomly from zero to 9.6 milliseconds in either the left or right eye's picture. Interchanging the delay means interchanging the pseudo-random noise generators to the separate video inputs of the monitors and also the scanning synchronisation inputs. To avoid disturbance to the subject whilst this is being done the monitors are allowed to "free-run" with no video input and with a uniform brightness equal to the average

brightness of the random dot pattern.

In every experiment reported so far, it was necessary to match the brightness for each eye at the viewing polaroids. In this experiment it is particularly important as variation in brightness casuses variations in the transmission times from the retina to the binocular fusion points in the visual cortex. To make sure that the results were not affected by imperfect matching of brightness each subject did the experiment twice with the viewing polaroids interchanged the second time. Testing all the subjects once took about a week and in this time half the subjects did the test with the viewing polarcids positioned normally and the other half performed the test with the polaroids interchanged. The effect of changing over the polaroids can then be found from the results.

Eighteen subjects were used in Experiment 12. A small square in the centre of vision was presented to them at two different disparities, 6.8' and 20.4', which could be either convergent or divergent and their task was to ascertain whether the square was closer to them than the fixation point or further away. The square in addition, was presented with three possibilities of interocular delay. These were the left eye's picture lagging or leading the right eye's picture by 9.6 milliseconds and thirdly no delay between the two pictures. Three delays multiplied by four disparities (two magnitudes each presented at convergent or divergent disparity) made twelve treatments and these were presented to the subject seven times each making a total of eighty-four samples. The random order of these samples was different for each subject. The sequence length that the subject actually received was a hundred as the first sixteen were discarded. The subject was informed about the different binocular disparities and was shown the square in its four positions but was not informed about the interocular delay.

The interocular delay of 150 lines or 9.6 milliseconds was chosen after a number of preliminary tests on a smaller group of subjects (none of whom did Experiment 12) designed to find an interocular delay at which results might become significant. The results of Experiment 12 are shown on Fig.8.1 and 8.2 and the experimental conditions are summarised on Fig.8.2.

As in previous experiments the two types of error are analysed separately but the analysis of variance is now as for a factorial experiment with a randomised group design. The three factors are A (disparity with two levels), B (interocular delay with three levels) and C (orientation of polaroids with two levels). A summary of the analysis of variance is shown in Table 8.2. For both types of error the treatments show a significant F ratio as does the main effect A (magnitude of binocular disparity). However, the main effect B (interocular delay) is only significant for type 1 errors.The main effect C (orientation of polaroids) is nonsignificant for both types of error as is its interactions with A and B. The interaction of A with B is only significant for error 1.

Increasing the magnitude of the binocular disparity increases both types of error. Changing the polaroids over has no effect whatever on the experiment as it should not if the brightnesses at the viewing polaroids are matched correctly. The effect of interocular delay on error is shown graphically on Fig.8.3 A. For the smaller disparity the addition of interocular delay to either the left or right eye causes an increase in error. As indicated by Table 8.4, Fig.8.2, the total of errors with interocular delay of 9.6 milliseconds are significantly greater than errors with no delay but there is no significant difference between the effect of a delay in the left eye's picture and a delay in the right eye's picture. However, at the larger binocular disparity the error totals at all three levels of

the delay factor B are significantly different from each other as indicated in Table 8.4. The greatest error rate is caused by the right eye's view lagging behind the left eye's view and the smallest error rate occurs with simultaneous presentation (an interocular delay of zero). That interocular delay acts differently with different binocular disparities is indicated by the significant A x B factor for the error type 1. Table 8.3, Fig. 8.2, demonstrates in another way the effect of disparity and interocular delay. Totals for either type of error do not differ significantly from each other for the smaller disparity nor for the larger disparity with the right eye's view lagging. However, an error bias does exist for simultaneous presentation and a left eye's view lagging at the larger disparity.

From the argument given earlier it was expected that the effect of interocular delay would be different for small and large binocular disparities and different for large convergent and divergent disparities. The results show that interocular delay does not react differently for different magnitudes of disparity providing these are convergent. For divergent disparities interocular delay increases the error rate but there is no significant difference between the error rate for the right eye's view leading and for the right eye's view lagging. The higher error rate for the lagging right eye at a large convergent disparity suggests that priority is given to the left hemisphere when double representation exists, or that projections from the right hemisphere to the left are stronger than projections from the left hemisphere to the right. However, again following from the reasoning given earlier this would imply that at a large divergent disparity a higher error rate should exist for leading eye's right view. This was not found. It could be argued that some constant bias exists (due perhaps to eye dominance) and that this bias

may be increased but not entirely reversed. However, if this bias were due to something like eye dominance it is odd that this is not shown for the smaller binocular disparity. Alternatively, it could be argued that since perception at divergent disparities is so poor with no interocular delay, that the application of interocular delay has little extra effect.

8.3. THE PULFRICH STEREO-PHENOMENON FROM RANDOM DOT STEREOGRAMS WITH INTEROCULAR DELAY.

When a random dot sterogram consisting of one plane at zero disparity is made from dynamic noise and presented with interocular delay the following is observed. Clusters of dots are seen moving outside the reference plane which lies through the point of fixation. When the right eye's view is lagging the left, those clusters nearer to the observer than the fixation point move from left to right whilst those further away on the other side of the reference plane move from right to left. At the extreme left and right ends of the random dot pattern the two paths of motion meet so that the complete trajectory of the clusters of dots is elliptical. The moving clusters form the boundaries of a transparant elliptical cylinder whose axis is a vertical line though the fixation point when this is placed in the centre of the random dot pattern. The clusters move together around the trajectory so that no relative movement is observed between the clusters on one side of the reference plane. One axis of the ellipse is the horizontal dimension of the random dot pattern. The other axis which is on a line from the observer through the centre of the dot pattern varies in magnitude according to the interocular delay. An increase in this delay increases this axis of the ellipse. The other effect of increasing the interocular delay is to decrease the apparent motion of the clusters of dots and to make these clusters larger and fewer in number.

The description given by many subjects on being shown this effect was "like a snowstorm". It takes only a few seconds to perceive the full effect, this time increasing as the interocular delay increases. When the interocular delay is increased beyond a certain point it is not possible to perceive the effect at all. At this point the appearance of the pattern is like that obtained by binocularly viewing two independent visual noise sources. Apparent movement is restricted to two dimensions as for an interocular delay of zero. Although the classical Pulfrich stereophenomenon is well known this will be reviewed before further discussion of the special random dot effect.

The classical illusion was discovered by Pulfrich over fifty years ago (PULFRICH, 1922) and is demonstrated by Fig.8.4.A. When a simple pendulum is observed binocularly with a filter over one eye to reduce illumination the pendulum bob appears to move in an elliptical path. The direction of rotation is reversed if the optical filter is transferred to the other eye.The magnitude of the stereoscopic effect increases with the density of the filter used. The effect does not exist when there are no other objects (other than the pendulum) in the visual field. It is usually stated (OGLE, 1962) that the effect is independent of the point of fixation. That is, the effect is observed whether the eyes track the pendulum bob or whether they fixate on a fixed point in the visual field. However, a recent paper (ROGERS et al, 1974) suggests that the effect disappears if the eyes track the pendulum bob so that its image always falls on the respective foveas.

The normal explanation for the Pulfrich effect is as follows. Retinal luminance affects the time delay between retinal stimulation and cortical stimulation. A decrease in luminance causes an increase in this delay. If the filter is placed over the right eye then as far as the visual

cortex is concerned the right eye sees what the left eye has seen earlier. From the geometry of Fig.8.4.A the simple pendulum is observed as a conical pendulum.

The delay line explanation given above has been confirmed by an experiment with random dot stereograms (JULESZ & WHITE, 1969). They produced a random dot stereo movie with an interocular delay of one frame. Without this phase difference successive random dot stereograms, that formed the movie, yielded a square area of dots in front of the reference plane. The movie was run at several speeds and illumination and stereopsis could always be recovered by reducing the illumination of the leading eye. There are other studies of visual delay as a function of luminance (WILSON & ANSTIS, 1969).

The description of the classical effect is very similar to the random dot Pulfrich phenomenon described earlier except in one respect. In the classical case, interocular delay does not affect the time for one complete cycle whilst in the random dot case initial observations suggest that it does. An experiment was performed to check these observations objectively.

A blank square, each side subtending a visual angle of 30' of arc, was cut into each random dot pattern. Its horizontal position was modulated by a triangular wave so that it traversed the horizontal extent of the pattern at uniform speed reversing its direction as it arrived at each end. Its vertical position was midway between the upper and lower boundaries and it was presented at zero disparity so that it moved in the reference plane. Subjects were presented with a random dot pattern at some interocular delay and adjusted the frequency of the triangular wave until the black square moved across the picture at the same speed as the clusters of dots.

The triangular wave was chosen to modulate the position of the square in preference to any other wave (e.g. a sine wave) because the author

considered that a constant speed stimulus was the least presumptious of the possibilities available. A sine wave seemed particularly unsuitable as it appeared to the author that the clusters of dots increased their speed as they approached the horizontal limits of the dot pattern. The size of the dot pattern was 10.3° vertically by 5.95° horizontally and the illumination was set at 1 lumen/square foot for each eye. The usual clock frequency of 5 MHZ was used.

Five interocular delays were used in this experiment ranging from three hundred television lines or 19.2 milliseconds to eleven hundred lines or 70.5 milliseconds. The right eye's view always lagged behind the left eye's view. Each subject was presented with twenty-five samples; each magnitude of delay being used five times and in random order. When the subject was satisfied that the black hole was moving at the same average speed as the clusters of dots he signalled his satisfaction to the experimenter who read off the frequency from a digital frequency counter connected to the waveform generator. The experimenter then asked the subject to adjust the speed of the black square to its lowest value before the next sample was presented. The dial on the waveform generator was covered with black tape so that the subject could not read the setting. The oscillator was positioned close to the subject so that he could adjust the frequency whilst observing the random dot pattern. The results for two subjects are shown on Fig.8.4 B.

Both subjects show a maximum speed at thirty-two milliseconds interocular delay and a steady decrease in speed for greater delays. No significance is put on the sub-optimal value at 19.2 milliseconds because it seemed to the author that the Pulfrich effect was fairly weak here, with the ordinary random motion of dynamic noise dominating perception, and that it was difficult to match the speed of the black square with

what Pulfrich motion could be observed.

Otherwise the results confirm the initial observation that the speed of the elliptical motion decreases as interocular delay increases.

Another experiment was performed to ascertain the limits of interocular delay at which the effect could be observed. The subject was presented with a random dot pattern with some interocular delay either in the right or in the left eye's view. He was asked to record the direction of elliptical motion. If at one magnitude of interocular delay he was able to record five correct answers in a row the delay was increased or decreased (depending upon whether the upper or lower threshold is being sought) to make the next samples more difficult. Both thresholds were approached from below and above simultaneously and the experimenter presented samples from any of the four paths in a random manner so that the subject would not get the impression he was approaching a threshold. The effect was found to exist from a delay of fifty lines (about three milliseconds) to a delay of 1450 lines (about ninety-three milliseconds) after testing one subject three times. The illumination for this test was 1 lumen / square foot for both eyes and the size of picture was 10.5° vertically by 5.95° horizontally. A clock pulse of 5 MHZ was used.

Presenting the dynamic noise with interocular delay for only a brief time (as in Experiment 12) it was found that the direction of motion correctly identified when only three frames were presented with an interocular delay of two frames. Little significance can be placed on this result however as the subject could easily distinguish between a delay in the left or right eye's view by noting which eye saw the stationary picture change to a dynamic picture first.

A further observation which is of interest is that when the interocular delay was large (e.g. about eighty milliseconds) and the clusters

of dots large and slow moving , sharp jerking movements of the head caused the pattern of clusters to shatter. The effect was like that of dust particles suddenly receiving a gust of air. This was not observed at smaller interocular delays.

There are two questions to be answered in the explanation of the effect. It is necessary to explain why it occurs and also why the elliptical movement slows down as interocular delay increases. As regards the first point it must be noted in studies of interocular delay and random dot stereograms reported previously (JULESZ & WHITE, 1969) the Pulfrich effect of swirling dots was not observed. However, in the above cited publication the dot density was sixty-five times less than in the experiment reported here. The horizontal extent of the dot pattern was 30^{o} of arc instead of 10.3^{o} used here and the width of each dot was almost four times greater. Furthermore a quarter of the area of the dot pattern was at some non zero disparity.

When a dynamic dot pattern is viewed the dots appear to move about randomly in all directions. The movement observed is apparent movement which results from closely spaced sequentially flashed dots (BIEDERMAN-THORSON et al, 1971). Except at the edges dots will appear to move from left to right and right to left in equal numbers. If the right eye's view is delayed those moving from left to right are seen in front of the fixation point and those moving from right to left are seen behind. The increase in apparent speed resulting from closely spaced sequentially flashed dots situated in the periphery rather than the centre of the visual field reported in the above cited publication could explain why the clusters of dots appear to travel faster at the extremes of the elliptical path. The greater number of dots and their smaller size compared to an earlier experiment (JULESZ & WHITE, 1969) would result in a better apparent movement effect.

For the Pulfrich effect to exist there must be movement and an interocular delay. If the movement is apparent movement in a dynamic noise pattern then its speed will not vary with interocular delay. Noting that increasing the interocular delay from 32 to 70.5 milliseconds almost halves the apparent speed there is the possibility that the interocular delay itself is responsible for the apparent motion.

Apparent motion may certainly be observed from dichoptic stimulation as demonstrated by the horizontal flicker observed with stereograms presented non-simultaneously and at a repetition rate below the critical fusion frequency for stereoscopic vision (EFRON, 1957). In this case for a given binocular disparity the speed is inversely proportional to the interocular delay. However, it is difficult to see how a Pulfrich effect could result from this since the effect must surely require monocularly perceivable movement in addition to an interocular delay. In addition there is no binocular disparity in the centre of the visual field and hence no movement.

A second possibility is that each eye sees in addition to its own picture a little of the other eye's view (i.e. there is "visual crosstalk") This crosstalk cannot be derived from the monitors themselves since interocular delay ensures that the video signals are entirely out of phase, but it could result from imperfect orientation of the polarising filters. However, with the right eye's monitor turned off no trace of any dot pattern can be seen by the right eye. With both monitors turned on at an interocular delay which enables apparent motion to be observed by superposition of the two pictures (section 6.1) no apparent motion can be observed looking through the viewing polaroids. If significant visual crosstalk did exist the apparent motion seen monocularly, though depending in part on the interocular delay, would be different for each eye. The delta movement of Korte (GRAHAM, 1965,p.581 and KORTE, 1915) is a reversed apparent

movement which occurs when the second object flashed is at a greater brightness than the first. The difference in retinal latency results in the second object reaching the cortex first and hence a reversal of apparent motion. If crosstalk existed between random dot patterns the following would result, if the "leading" pattern was brighter the apparent speed would be reduced whilst if the lagging pattern was brighter apparent speed would be increased or reversed. Visual crosstalk though possible imperfections in the polarising filters is thus not an adequate explanation for the observed Pulfrich effect.

If, as suggested earlier, the monocularly perceivable movement that causes the Pulfrich effect, when interocular delay is added, is the apparent motion of random dots from one random dot pattern, a possible mechanism for slowing down the Pulfrich elliptical motion is an increase in the stereoscopic summation time. If there is an interocular delay of one frame then there exists no correlation between frames simultaneously presented to the left and right eyes. If the stereoscopic summation time, which may be considered as the time constant of a low pass filter that accepts the visual inputs from each eye prior to binocular combination, is much less than the frame repetition period, then there will be no correlation between the left and right eye inputs to the point of binocular fusion. Perception will then be as if the two eyes were viewing independent noise sources. If, however, the stereoscopic integration time is much greater than the frame repetition period, several frames of noise will be integrated together and the binocular correlation will increase. It is possible, though to the author's knowledge it has never before been suggested, that the system of binocular fusion is an adaptive process. As the interocular delay increases the stereoscopic summation time might increase in order to retain signigicant correlation between the signals derived

from the two eyes prior to binocular fusion. Interocular delay must somehow be observed in magnitude and direction and the binocular fusion process will adapt itself to lessen the effect of the delay.

If the apparent movement is extracted after the low pass filter with the time constant T, the stereoscopic summation time, then an increase in T will cause the clusters of dots to be larger and their movement slower. Low pass filtering of the sequence of frames smooths out their differences so that instead of small dots performing sharp jerky movements aggregates of dots move about rather sluggishly.

Evidence for this idea of an adaptive process is in the observation reported in this section that sharp movements of the head at a large interocular delay casuses the percept of slowly moving clusters to shatter. If what is observed is due to frames of noise presented in the past, a sharp movement of the head destroys the correspondence between a particular point on the retina and what is in the visual memory (the low pass filter with time constant T) after having been stimulated by this point on the retina in the past. In the next section an experiment is performed to test the hypothesis of an adaptive process for binocular fusion.

8.4. A THRESHOLD EXPERIMENT WITH INTEROCULAR DELAY.

In any communcation channel where the signal is frequency bandlimited an improvement in signal to noise ratio may be obtained by filtering out all noise that lies outside the signal band. If the signal is restricted to zero frequency (d.c. in electrical terminology) then the ideal filter is a perfect integrator. If the eyes are viewing a stationary stimulus imbedded in a noisy television picture the judgement, as to the characteristics of the object, that the observer may make depends upon the filtering ystem of his eyes and visual cortex. The best approach for a

stationary object is to integrate successive television frames and take a "running" mean. However, any movements of the object will be smeared out by this process and so a compromise must be made between noise immunity and movement sensitivity. Experiment 13, which is described in this section, tests the hypothesis that the summation time of binocular fusion varies with interocular delay. The binocular fusion system is modelled as a first order low pass filter with a time constant equal to the summation time. The use of threshold experiments with stimuli embedded in noise as a means to finding the summation time is not new. It was suggested by Gregory (GREGORY, 1955) to calculate the change of retinal summation time with luminance.

A very simple model is used to model the binocular system and is shown in Fig.8.5. The retina is given a time constant a which depends upon the average luminance and is fixed throughout the experiment. Binocular fusion at the visual cortex is preceded by a low pass filter of time constant b which it is suggested may vary. The separation of the two low pass filters is supported by the work of Efron (EFRON, 1957) who confirmed the separate nature of stereoscopic and monocular critical fusion frequencies. After passing through both low pass filters the signals are added together. If independent noise is added in each channel the combination of the two noise degraded signals results in an improvement in the signal to noise ratio by a factor of $\sqrt{2}$. This is so since the mean of two independent samples of the same event drawn form a population of variance σ^2 yields a new population of identical mean to the first but having a variance of $\sigma^2/2$. That binocular combination in the cortex is capable of producing this $\sqrt{2}$ improvement in detection thresholds has already been shown (CAMPBELL & GREEN, 1965). The coding of the retinal response into nerve impulses and their subsequent decoding into decisions taken by the observer is not in-

cluded in the model. The model is meant to represent the overall passage of a signal up to stereoscopic fusion. This is distinct from monocular vision where the time constant b will not be involved. The two channels in Fig.8.5 represent optic fibres from the left and right eyes. The delay T is the interocular delay and is the phase difference of the video signals that feed the two TV. monitors.

As stated above, the average of two noise processes of variance σ^2 yields a new noise process of variance $\sigma^2/2$ if the two noise processes are independent and σ^2 if they are identical. If the correlation between the two noise processes lies between these two extremes then it can be shown (Appendix 2A) that the new variance is given by,

$$\sigma_z^2 = \sigma^2 \frac{(1+\rho)}{2} \qquad (8.1)$$

where σ_z^2 is the new variance and ρ is the normalised correlation coefficient. The coefficient ρ is dependent upon the interocular delay T and the time constants a and b of Fig.8.5. An increase in T will decrease ρ and hence σ_z^2, the effective variance of the noise after binocular combination. If b is constant, the stimulus level at which detection is possible, will decrease as interocular delay increases. When the delay T becomes much greater than the time constants a and b, so that smoothing by these filters is insufficient to cause significant correlation between the noise and its delayed version, the stimulus level should asymtotically approach $1/\sqrt{2}$ of its level for zero interocular delay.

The effect of an increase in b as interocular delay increases is two-fold. Firstly, it increases the correlation coefficient ρ and therefore tends to increase the stimulus level for detection. Secondly, an increase in b results in more noise being filtered out and therefore tends to reduce the stimulus level. Because the time constant of the TV screen is much less

than a, the retinal time constant, and the period of the pseudo-random sequence is much greater than a, the power spectrum of the visual noise (Appendix 1.E) may be considered flat. It is shown in Appendix 2.B that in the case of white noise the change in stimulus level at which detection occurs as the time constant b changes from b_0 (with zero interocular delay) to b_T (with interocular delay of T) is given by,

$$\gamma = \sqrt{\left(\frac{1 + b_0/a}{1 + b_T/a}\right)} \qquad (8.2)$$

The total effect on the stimulus level when the interocular delay changes from zero to T is then

$$\mathcal{E} = \sqrt{\left(\frac{1 + \rho}{2}\right)\left(\frac{1 + b_0/a}{1 + b_T/a}\right)} \qquad (8.3)$$

when the change in correlation is also taken into account.

The term γ may vary between $\sqrt{(1 + b_0/a)}$ and zero. It is therefore possible that the fraction $\mathcal{E}$ may fall below $1/\sqrt{2}$. If this is so then it would mean that stimulus detection for noise applied with some finite interocular delay T would be better than for independent noise applied to each eye. If the system of binocular fusion is adaptive with respect to interocular delay the following behaviour is expected for detection of a visual stimulus imbedded in noise. If the stimulus level for detection with zero interocular delay is unity then this level falls below unity as interocular delay is increased. When the interocular delay T is such that a significant change in the time constant b occurs (e.g. by a factor of two a three) the stimulus level falls below $1/\sqrt{2}$. As the delay T is increased further the adaptive system ceases to function, the time constant b returns to b_0 its value for zero delay, and the stimulus level jumps to $1/\sqrt{2}$. If however, the binocular fusion process is not adaptive and b remains constant for all interocular delays then as T is increased the

stimulus level falls monotonically to $1/\sqrt{2}$ the level for independent noise in each eye.

The relation between the correlation coefficient ρ and a, b, and T may be found by an application of linear system theory. With the notation given in Fig. 8.5

$$S_2(t) = S_1(t-T) \tag{8.4}$$

where S_2 and S_1 represent only the visual noise. The stimulus is a d.c. component added onto S_1 and S_2. The correlation $\Phi_{12}(\tau)$ between S_1 and S_2 is given by,

$$\Phi_{12}(\tau) = \underset{T\to\infty}{\lim} \frac{1}{2T} \int_{-T}^{+T} S_1(t)\, S_2(t-\tau)\, dt \tag{8.5}$$

which using (8.4) becomes,

$$\Phi_{12}(\tau) = \Phi_{11}(T+\tau) = \underset{T\to\infty}{\lim} \frac{1}{2T} \int_{-T}^{+T} S_1(t)\, S_1(t-T-\tau)\, dt \tag{8.6}$$

If $h(t)$ is the impulse response of the complete channel and $n(t)$ is the noise input then

$$S(t) = \int_{-\infty}^{\infty} h(u)\, n(t-u)\, du \tag{8.7}$$

It is shown in Appendix 2C that by the substitution of (8.7) into (8.6) $\Phi_{11}(T+\tau)$ becomes

$$\Phi_{11}(T+\tau) = \int_{-\infty}^{\infty} h(\lambda)\, h(\lambda-T-\tau)\, d\lambda \tag{8.8}$$

Using the Wiener theorem of autoocorrelation for $\tau = 0$,

$$\Phi_{12}(0) = \Phi_{11}(T) = \int_{-\infty}^{\infty} \left|H(j\omega)\right|^2 \exp j\omega T\, \frac{d\omega}{2\pi} \tag{8.9}$$

where $H(j\omega)$ is the Fourier Transform of $h(t)$. For a channel consisting of two low pass filters of time costants a and b, $H(j\omega)$ is written as

$$H(j\omega) = \frac{1}{(1 + j\omega a)(1 + j\omega b)} \qquad (8.10)$$

It is shown in Appendix 2C that sustitution of (8.10) into (8.9) and evaluation of the integral leads to

$$\Phi_{12}(0) = \frac{be^{-T/b} - ae^{-T/a}}{2(b^2 - a^2)} \qquad (8.11)$$

The normalised correlation coefficient ρ then becomes

$$\rho = \frac{be^{-T/b} - ae^{-T/a}}{b - a} \qquad (8.12)$$

As b approaches a, ρ behaves as

$$\rho = e^{-T/a}(1 + T/a) \qquad (8.13)$$

For both (8.12) and (8.13), excluding negative T, ρ has a maximum value of unity when T is zero and falls to zero as T becomes much greater than a and b.

The stimulus used in Experiment 13 was a grating of vertical bars superimposed upon the visual noise. The method by which the video noise signal may be modulated by another signal was described in chapter 5. A portion of the modulated video signal is drawn in Fig.8.6A. Vertical bars were a convenient video stimulus to use because these could be conveniently generated by dividing down the line synchronisation pulses. The system for introducing interocular delay into the TV. monitors leaves the line synchronisation the same in both monitors and so there is no interocular spatial phase difference between the stimuli. This is important as it has been shown (HENNING & HERTZ, 1973) that such a phase difference will lower

the threshold for detection. Twelve bars were visible on the picture which gave a spatial frequency of just over 1 cycle/degree. The spatial frequency of the bars could be expected to affect perception (CAMPBELL & GREEN, 1965; POLLEYN & ROEHRIG, 1970). The latter reported that the "signal to noise threshold, in addition to being strongly dependent on the bar pattern frequency, is also dependent on the r.m.s. value and the frequency distribution of the noise as well as the difference between the bar pattern frequency and the medium frequency of the noise". However, since the purpose of Experiment 13 is only to follow the relative change in stimulus level necessary for perception as interocular delay is varied these considerations are not relevant. The most appropiate visual noise form to mask a vertical grating is another grating of thinner vertical lines of random brightness (JULESZ, 1971) but again, for the purposes of Experiment 13, visual noise of any sort is adequate.

The square wave that generates the vertical grating was varied in strength by a potentiometer and its value at the modulation input of the video amplifier was measured by a digital voltmeter (Simpson 460). Because the signal modulates the noise instead of being added to it the total power in the modulated waveform is, in the notation of Fig. 8.6A,

$$\text{Total Power} = \tfrac{1}{4}\left[\left(V+\tfrac{1}{2}S\right)^2 + \left(V-\tfrac{1}{2}S\right)^2\right] = \tfrac{1}{2}\left[V^2+\tfrac{1}{4}S^2\right]$$

The signal power may be found by considering the power at the signal frequency in the spectrum of the modulated waveform. This is the product of the d.c. level of the unmodulated noise and the signal itself. Thus

$$\text{Signal Power} = \left(\tfrac{1}{2}V\right)^2.(S/2V)^2 = S^2/16 \qquad \text{and}$$

$$\text{Noise Power} = \text{Total Power} - \text{Signal Power} = \tfrac{1}{2}\left(V^2+S^2/8\right)$$

and the r.m.s. signal to noise ratio may be written

$$\frac{\text{SIGNAL}}{\text{NOISE}}\ (\text{r.m.s.}) \propto \frac{S}{V\sqrt{(I+S^2/8V^2)}} \approx \frac{S}{V(I+S^2/16V^2)} \approx \frac{S}{V}\ ,\ \frac{S}{V}<I/4$$

Therefore the signal to noise level at which detection occurs is approximately proportional to S the stimulus level (Fig. 8.6A).

level. Ideally a linear transformation from the video signal to brightness on the TV.screen is required. This was possible with an S/V of about 1/10 and the V level set so that with S=0 the "white" dots were actually medium grey.

Ten subjects were used in this experiment. Each subject's threshold was found in eight different conditions. The interocular delay was varied from zero to 120 milliseconds in steps of 20 milliseconds. In addition the threshold was found for independent noise applied to each eye. A staircase method was employed to find the thresholds. The vertical bars were shown to the subject initially and then the noise was presented to the subject with or without the bars added. The subject was asked to judge whether the vertical grating was present or absent. He had to get five in a row of a random sequence correct before the stimulus level was reduced further. The experimenter randomly moved from one of the eight conditions to another so that each threshold was approached simultaneously. The threshold stimulus level for each treatment was divided by the level obtained for zero interocular delay leaving a stimulus level of unity for the latter. The average readings of the ten subjects are shown in Fig(8.6)together with a summary of the experimental conditions. The effective change in signal to noise ratio necessary for perception is plotted against interocular delay in Fig(8.7A).

The results shown in this graph are rather disappointing. There is no range of interocular delays at which perception of a stationary stimulus is superior to perception with independent noise in each eye. The $1/\sqrt{2}$ improvement is indeed obtained in this latter case but the application of interocular delay results in a rather slow approach to this value. The behaviour that was predicted for an adaptive system is not found. In the calculations to find b it is first assumed that b remains constant

as interocular delay varies. If however, b increases with the delay then the b' calculated by considering only the $\sqrt{\frac{1+\rho}{2}}$ term in equation 8.13 will show a steady decrease as the interocular delay increases. The time constant b is calculated on this basis and Table 8.5 in Fig.8.6 shows the results together with the effective standard deviations. The latter were calculated by considering the first order sensitivity of b with respect to the stimulus level necessary for perception. A value for a of 20 milliseconds was used for all calculations (FINK, 1957). The results for b are plotted on graph B in Fig.8.7. The mean value of b is 56 milliseconds and there is no overall decrease of b with interocular delay. It seems therefore that binocular fusion does not act as an adaptive system but maintains constant parameters as the interocular delay is varied. The mean value of b is sustituted into equations (8.12) and (8.3). The predicted curve for the signal to noise ratio necessary for perception is plotted with the experimental results on Graph A, Fig(8.7).

The two curves of Graph A follow each other closely. The two time constant model of Fig.8.5 would seem to explain the experimental results adequately without any adjustment required for an adaptive time constant b. Although, as will be discussed in the next chapter, the calculated value of b of 56 milliseconds is supported by quite different experiments, the method described here cannot be considered a good one for measuring b. The calculated value of b is rather sensitive to small changes in $\mathcal{E}$, the signal to noise ratio at which perception is possible. Furthermore the retina must be modelled by a first order low pass filter whose time constant will also affect b. The important conslusions of this experiment are that, contrary to what was suggested in section 8.3, it is not possible to do better with interocular delay than with independent noise presented to each eye in the problem of perceiving a stationary stimulus masked by noise.

8.5. CONCLUSIONS.

Experiment 12, described in section 8.2, was partially successful in that the effect of interocular delay was different for the disparities used. This was predicted from a consideration of the effects of double representation of a central strip of retina in the cerebral hemispheres caused by the naso-temporal division. The results for the two types of possible errors were different as was predicted. The relation between the results of Experiment 12 and previous experiments is discussed in chapter 9.

The slowing down of the "Pulfrich" effect described in section 8.3 cannot be caussed by a system of binocular fusion in the visual cortex increasing its summation time for the neural inputs so as to compensate for interocular delay. This is clear from the results of Experiment 13 which are consistent with a non-ad ptive system of binocular fusion. It seems possible, therefore, that the apparent motion, which must exist for the interocular delay to distort the trajectory of motion, is caused by interocular delay itself. Non-simultaneous stimulation of the two eyes may certainly give rise to apparent motion as for example in the horizontal flicker described by Efron (EFRON, 1957). If this is the explanation of the effect then it is clear that the random dot Pulfrich phenomenon is quite different from the classical one where the speed of the object is quite independent of the interocular delay which only serves to modulate one axis of the elliptical trajectory.

If the results of Experiment 13 had been different and a reduction in stimulus strength less than $1/\sqrt{2}$ had been found for some finite interocular delay T, there might well have been some engineering applications. If the information in a video signal is reduced by low pass filtering, a decrease in horizontal resolution results. If the information is reduced by missing out several of the lines a decrease in vertical resolution

results. If, however, the video signal is sampled and only the sampled points displayed then the picture appears to have been degraded by impulse noise. In this way video bandwidth may be exchanged for a lower picture signal to noise ratio. If a means is found for increasing the effective signal to noise ratio at the visual cortex by inducing the brain to take an average of several frames the ill effects of the impulse noise might be reduced. A video sampling scheme in which this was tried is described in the next chapter and details are given in Appendix 3.

FIG.8.1 RESULTS OF EXPERIMENT 12

TABLE 8.1 AVERAGE SCORES FOR EACH FACTORIAL COMBINATION

		A_1						A_2					
		C_1			C_2			C_1			C_2		
		B_1	B_2	B_3	B_1	B_2	B_3	B_1	B_2	B_3	B_1	B_2	B_3
E1	$\bar{X}_k$	1.33	0.42	1.33	1.50	0.67	1.38	0.96	0.50	2.61	1.72	0.94	2.78
E1	S^2_k	2.00	0.38	2.00	1.50	1.06	1.55	1.04	0.62	2.61	1.86	0.99	4.77
E2	$\bar{X}_k$	1.11	0.83	1.50	0.83	0.94	1.50	2.50	3.22	2.11	2.61	2.50	2.55
E2	S^2_k	1.52	1.21	2.85	1.79	1.35	1.79	2.85	3.95	3.52	4.25	3.09	3.91

A_1 DISPARITY 2 BITS
A_2 DISPARITY 2 BITS
FACTORS A,B,C

C_1 VIEWING
C_2 POLAROIDS INTERCHANGED

B_1 LEFT EYE'S IMAGE DELAYED
B_2 NO DELAY INTRODUCED
B_3 RIGHT EYE'S IMAGE DELAYED

E1 ERROR 1 "NEARER" REPORTED AS "FURTHER"
E2 ERROR 2 "FURTHER" REPORTED AS "NEARER"

TABLE 8.2 ANALYSIS OF VARIANCE

	FACTORS	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F
ERROR 1	A	14.00	1	14.00	8.25*
	B	67.29	2	33.65	19.83*
	C	2.89	1	2.89	1.70
	A x B	18.34	2	9.17	5.40*
	A x C	0.79	1	0.79	
	B x C	0.40	2	0.20	
	A x B x C	0.12	2	0.06	
	TREATMENT	103.83	11	9.44	5.56*
	WITHIN TREATMENT	346.25	204	1.70	
	TOTAL	450.08	215	2.09	
ERROR 2	A	115.57	1	115.57	43.28*
	B	0.90	2	0.45	
	C	0.17	1	0.17	
	A x B	12.07	2	6.04	2.26
	A x C	0.00	1	0.00	
	B x C	2.52	2	1.26	
	A x B x C	4.70	2	2.35	
	TREATMENT	135.93	11	12.36	4.63*
	WITHIN TREATMENT	545.33	204	2.67	
	TOTAL	681.26	215	3.17	

*Significant at 5% level

FIG 8.2 CONDITIONS AND RESULTS OF EXPERIMENT 12

NUMBER OF SUBJECTS.....18(TESTED TWICE WITH VIEWING POLAROIDS INTERCHANGED FOR SECOND TEST)

SEQUENCE LENGTH.....2 DISPARITIES x 3 DELAYS x 2 LOCATIONS x 7 SAMPLES = 84

DURATION OF STIMULUS .....2 TV FRAMES (80 MILLISECONDS)

ILLUMINATION.....1.4 LUMENS/SQ.FOOT(MEASURED AT VIEWING POLAROIDS)

DIMENSIONS OF DOT PATTERN...8^{o} x 5.5^{o}

MAGNITUDE OF INTEROCULAR DELAY.....150 TV LINES(9.6 MILLISECONDS)

BINOCULAR DISPARUTY.....2 BITS AT 5MHz(6.8'),6 BITS AT 5 MHz(20.4')

STIMULUS.....1.58^{o} SQUARE IN CENTRE OF VISUAL FIELD

TABLE 8.3 VARIATION OF ERROR BIAS WITH DISPARITY AND INTEROCULAR DELAY

DISPARITY (BITS)	INTEROCULAR DELAY	BIAS (DETERMINED BY t TEST AT 5% SIGNIFICANCE LEVEL)
2	LEFT EYE	insignificant difference
2	NO DELAY	insignificant difference
2	RIGHT EYE	insignificant difference
6	LEFT EYE	ERROR 2 > ERROR 1
6	NO DELAY	ERROR 2 > ERROR 1
6	RIGHT EYE	insignificant difference

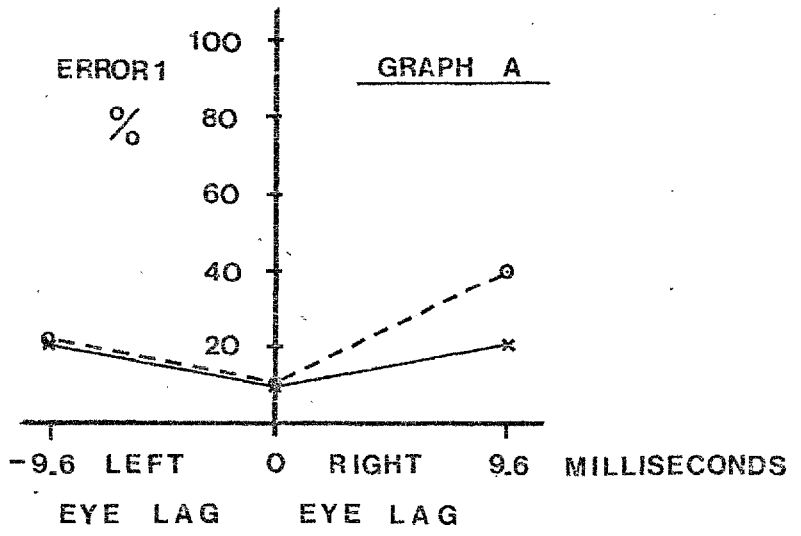
TABLE 8.4 EFFECT OF INTEROCULAR DELAY ON ERROR RATE

DISPARITY \ ERROR	ERROR 1			ERROR 2		
2 BITS	0.61 N	1.36 R	1.42 L	0.889 N	0.972 L	1.50 R
6 BITS	0.72 N	1.50 L	2.69 R	2.33 R	2.56 L	2.86 N

N,L,R. = NO DELAY,LEFT EYE'S IMAGE DELAYED,RIGHT EYE'S IMAGE DELAYED.
A LINE JOINING TWO SCORES INDICATES NO SIGNIFICANT DIFFERENCE (t TEST AT 5% SIGNIFICANCE LEVEL)

FIG.8.3 RESULTS OF EXPERIMENT 12

GRAPHS OF ERROR v INTEROCULAR DELAY



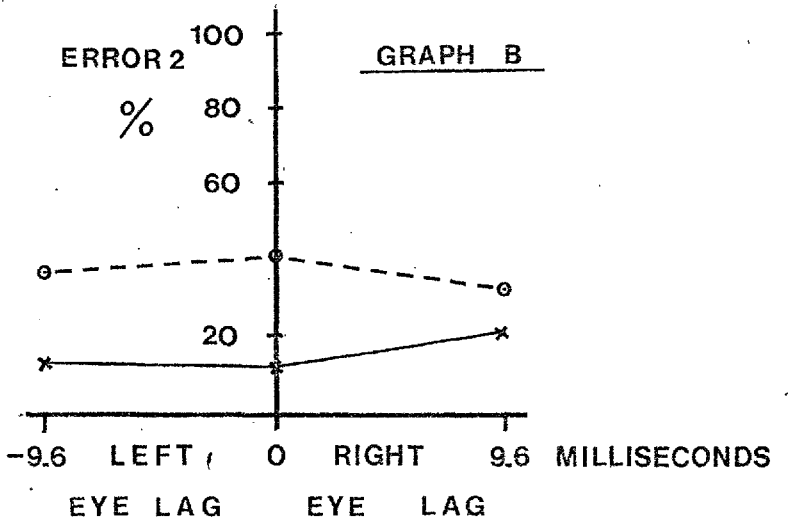


FIG.8.4A THE PULFRICH STEREOPHENOMENON

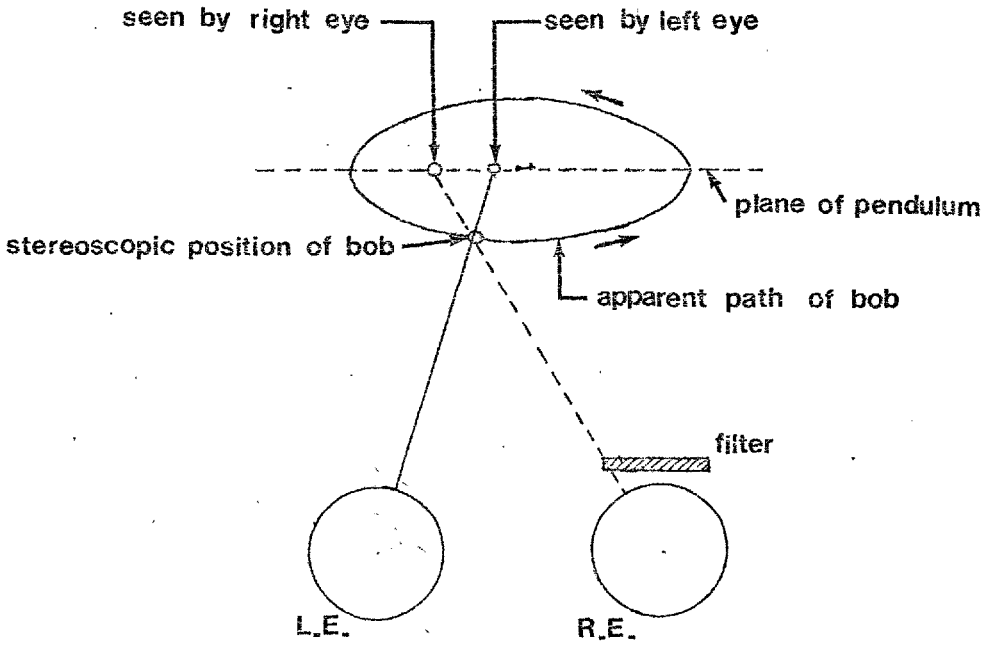


FIG.8.4 B MAGNITUDE OF "PULFRICH" MOVEMENT AS INTEROCULAR DELAY IS VARIED

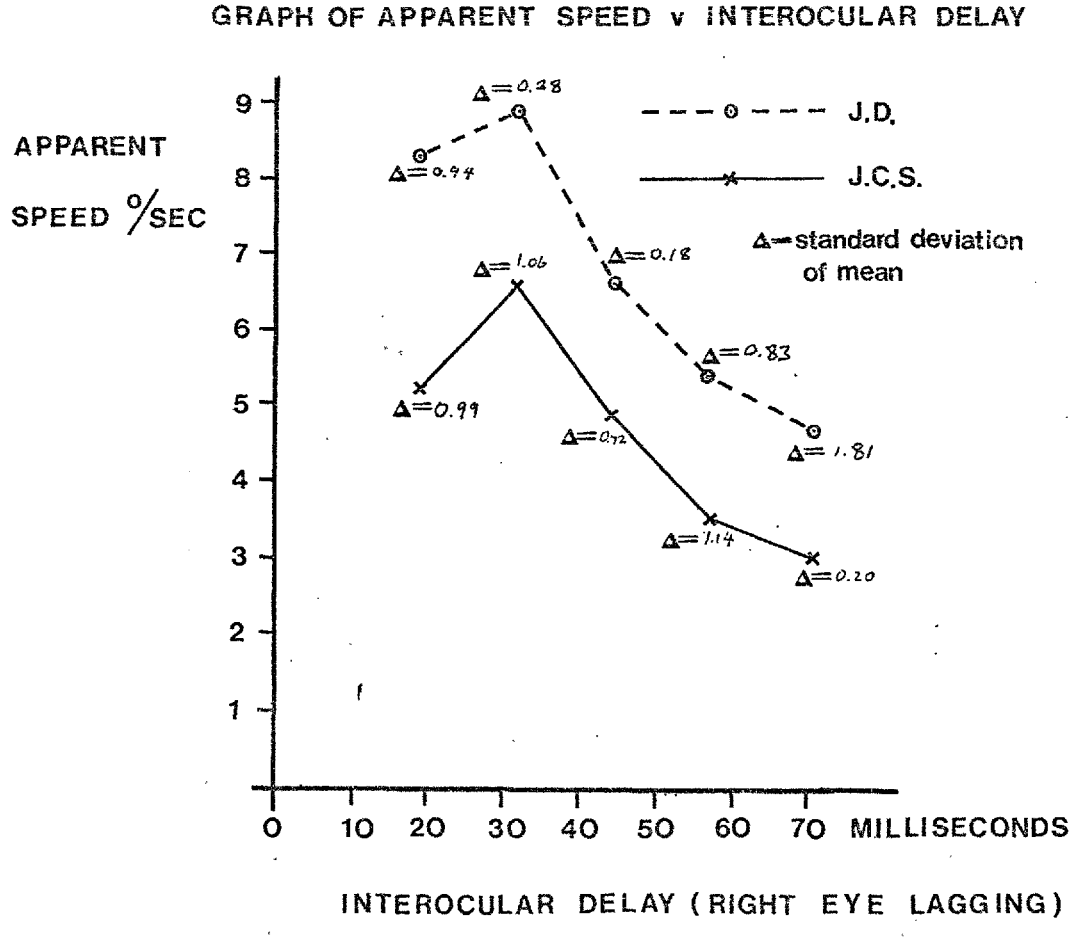


FIG. 8.5 A MODEL OF BINOCULAR COMBINATION FOR EXPERIMENT 13

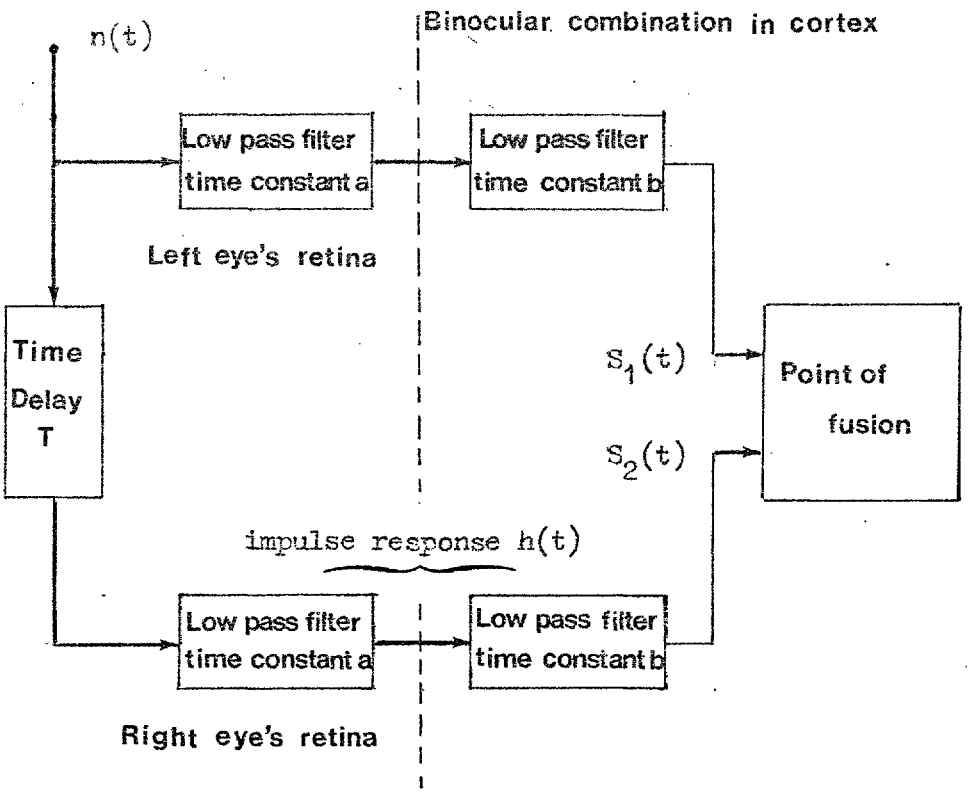
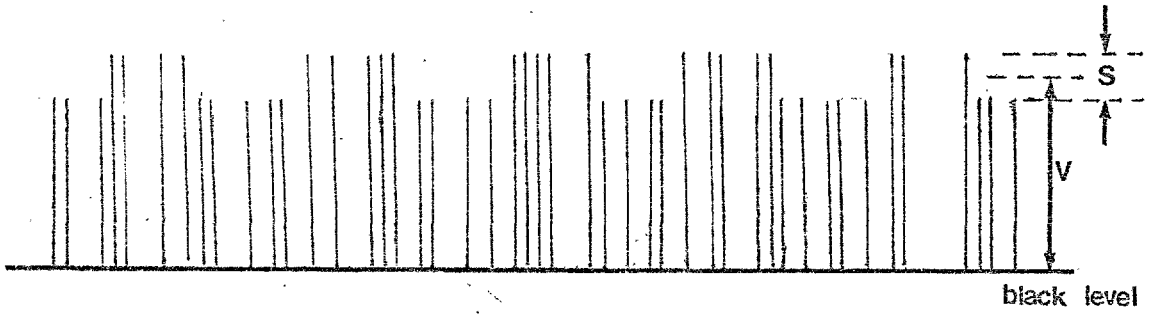


FIG.8.6 EXPERIMENT 13 : STIMULUS AND RESULTS

A. MODULATED VIDEO NOISE SIGNAL



B. EXPERIMENTAL CONDITIONS AND RESULTS OF EXPERIMENT 13

NUMBER OF SUBJECTS.....10

ILLUMINATION.....1.5 LUMENS/SQ.FOOT (MEASURED AT THE VIEWING POLAROIDS)

INTEROCULAR DELAY..... 0→120 MILLISECONDS IN 20 MILLISECOND STEPS (ALWAYS IN RIGHT EYE'S IMAGE)

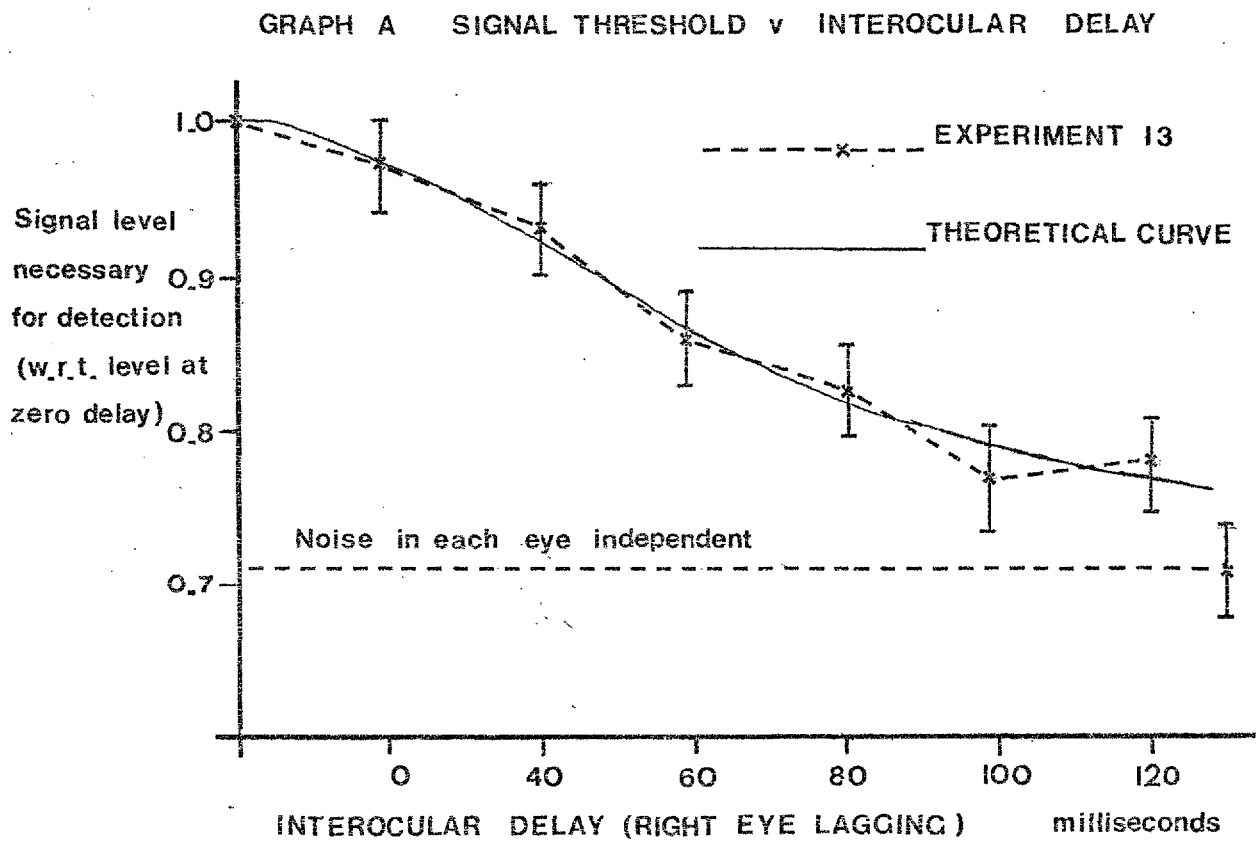
DIMENSION OF DOT PATTERN..... $10.3^{\circ} \times 5.95^{\circ}$

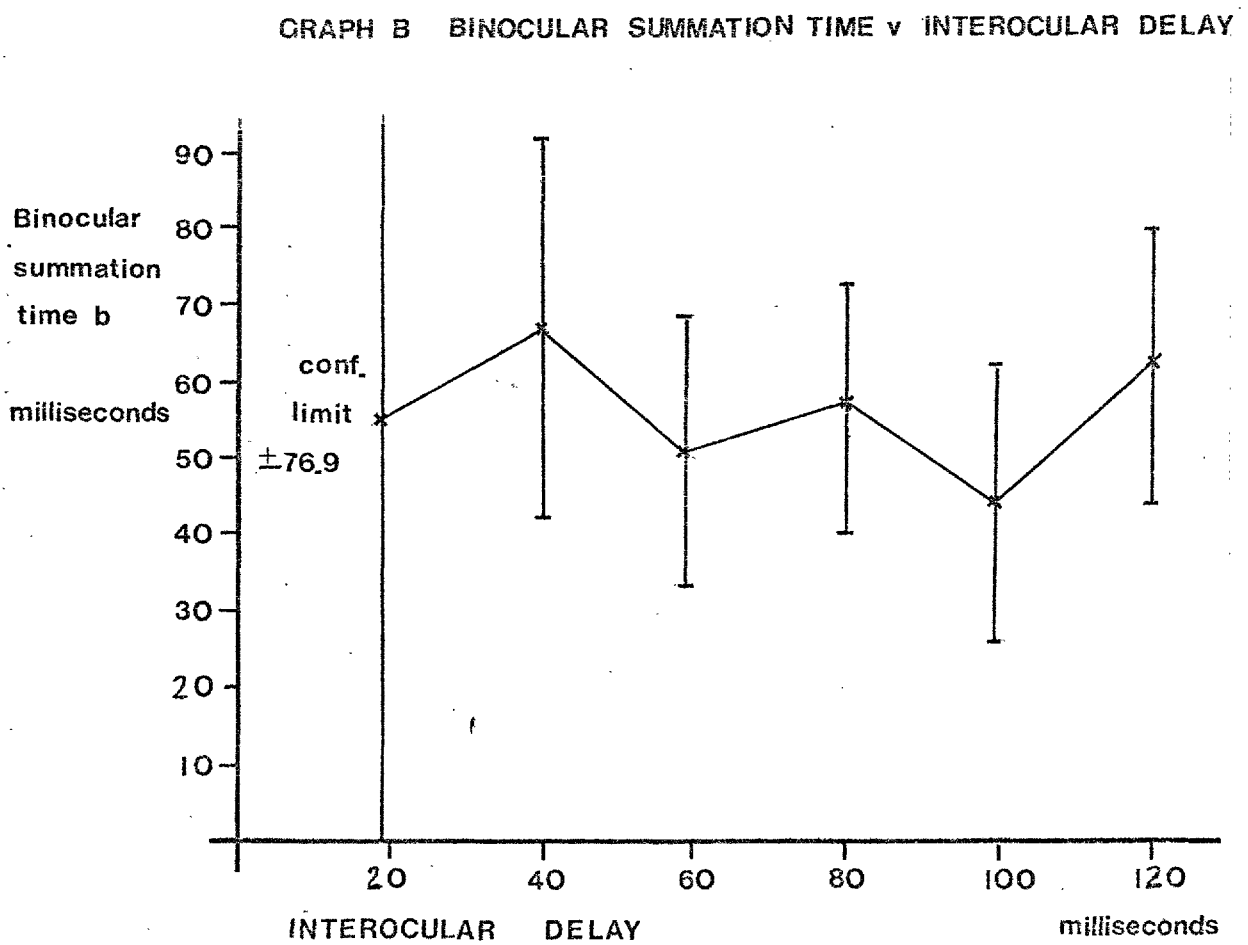
NUMBER OF VERTICAL BARS..... 12

TABLE 8.5 RESULTS OF EXPERIMENT 13

I.O.D. ms	0.	19.2	40.	59.2	80.	99.2	120.	ind. noise
Mean	1.0	0.97	0.93	0.86	0.83	0.77	0.78	0.71
S.D.of Mean		0.021	0.020	0.019	0.019	0.023	0.020	0.022
b(ms)		55.	67.	50.5	56.9	43.5	62.	
effective S.D.of b		46.8	17.51	11.80	10.28	12.16	12.17	

FIG. 8.7 RESULTS OF EXPERIMENT 13





Confidence limits in both graphs refer to 5% significance level

CHAPTER 9

CONCLUSIONS.

The experiments reported in chapters 6, 7 and 8 have revealed four separate asymmetries in stereoscopic vision. Under certain conditions observers are more likely to perceive a convergent disparity correctly than a divergent disparity of the same angular magnitude. This may be considered as an asymmetry of stereoscopic ability on a sagittal line through the point of fixation. Secondly observers are generally able to perform the operation of stereopsis better in their right cerebral hemispheres(objects in the left visual field) than in their left cerebral hemispheres(objects in the right visual field). Thirdly, a rectangle centrally located in the visual field with its longest side horizontal is more likely to be correctly located in depth relative to the point of fixation than the same rectangle also centrally located but with its longest side vertical. Finally a small object located in the centre of the visual field with a large convergent disparity and presented with interocular delay, has its depth relative to to the fixation point more correctly perceived if the right eye receives the "leading" image rather than the "lagging" image.

All these findings were made with random dot stereograms rather than classical stimuli. It is interesting to note that hemispherical asymmetry in problems of spatial localisation is much more evident with random dot stereograms than with line drawings(DURNFORD & KIMURA,1971).The presence of depth cues other than binocular disparity will mask any variations in ability of the brains mechanism of stereopsis as suggested by the inventor of random dot stereograms (JULESZ, 1971). Furthermore the experiments reported in this thesis on stereopsis in the centre of the visual field

can only be performed with high density dot patterns. If the dot density is low than a small area in the pattern that is marked out for some relative disparity to the rest of the pattern will contain so few dots that stereopsis is difficult to achieve. If it can only be achieved reliably when a long time of presentation is allowed so that convergence and divergence movements of the eye are possible, the experimenter cannot be sure of what part of the observer's retina he is stimulating and what binocular disparity a particular part of the stimulus gives rise to. From the results of work on vergence movements of the eyes (RASHBASS & WESTHEIMER, 1961) it is clear that 80 milliseconds, the standard presentation time used in the reported experiments in this thesis, is short enough for the experimenter to be certain of the binocular disparity and position of any stimulus presented. Another aspect of the method of presentation of a stereoscopic stimulus used is that there is no change in either overall retinal illumination or the general texture of the retinal image when a step change in binocular disparity is produced, and this is achieved without any monocular cues being available for depth perception. Experiment 12 (Section 8.2) used an original method of presentation to remove some of the problems encountered with interocular delay. If a fixed visual stimulus is presented first to one eye and then at a later time to the other there is certainly an interocular time difference between the arrival of the stimulus at the two retinae. However, if the duration of the stimulus at each retina is much greater than this time difference, then, from a cortical viewpoint , the interocular time difference disappears after a time because the visual stimulus does not change with time for its period of existence. This difficulty may be removed by making the duration of the stimulus much less than the interocular time difference but there are some circumstances where good perception demands a longer exposure to the stimu-

lus. In Experiment 12 a stimulus duration of 80 milliseconds is used with an interocular delay of about 10 milliseconds by using a dynamic noise pattern to present the step change of binocular disparity. It may be noted that other workers, who did not use this technique (WIST & GOGEL, 1965), have reported that there is negligible change in sterecacuity for interocular delays up to 32 milliseconds whereas the author found in Experiment 12 that for a convergent disparity of 6.8' performance was significantly worsened with an interocular delay in either eye of just under 10 milliseconds. Another aspect of the method of presentation of a stereoscopic stimulus used in experiments reported in this thesis is the stimulation of binocular disparity detectors (which are assumed to exist in the visual cortex) at all times. If the observer had been presented with a uniform grey sheet of the same average brightness as the random dot pattern then prior to the appearance of the random dot stereogram there should be little activity in the disparity detectors. In the author's method the observer gazes at a random dot pattern in a fronto-parallel plane through the fixation point so that his zero disparity detectors will be stimulated. According to the tuned detector theory (BISHOP, 1970, BLAKEMERE & HAGEN, 1972) disparity detectors that fire maximally for binocular disparities of magnitude a little greater than zero will be inhibited whilst those tuned to much larger disparities will fire freely at some sub-optimal level.

In considering the results of, for example, Experiment 3 which showed a significant tendency to judge large divergent disparities as actually convergent, there is always the possibility that these results are caused by some fault in the apparatus or in the experimental methods. It could be argued that the difficulty in perceiving divergent disparities is the difficulty of perceiving a "hole" in the reference plane with a second plane visible behind rather than an area placed on top of the reference plane.

However, if this is the reason behind convergent-divergent asymmetry it is difficult to see why this asymmetry should disappear for small disparities, for "holes" in the periphery rather than the centre of the visual field and for a horizontally aligned rectangle rather than a vertically aligned rectangle. The problems of visual "crosstalk" were completely eliminated as far as the monitors were concerned (chapter 4) and, by having the viewing polaroids fixed to the apparatus rather than to the observer, that which originated from imperfect polarisation of light was severely reduced. Again, because most experiments compared the results of two or more stimuli the results can only be explained as due to a faulty method by considering an interaction of apparatus idiosyncrasy with the stimulus variation. The author is confident that such possible idiosyncrasies that did exist played no part in the results.

The results of Experiments 1 - 12 will first be considered in terms of Julesz's dipole model for stereopsis (JULESZ, 1970), which was described in chapter 3, and then with reference to particular neurophysiological findings that have been reported. The dipole model was postulated largely on the basis of one experiment (FENDER & JULESZ, 1967) and it differs from the earlier difference field model (JULESZ, 1960) by possessing inertia and in particular by demonstrating hysteresis. This ought to make it suitable for discussing the dynamic aspects of stereopsis.

It should be said that although the action of two matrices of magnetic dipoles superimposed may have little resemblance to the action of several matrices of tuned binocular disparity detectors, the action of the brain in decoding the outputs of the disparity detectors to yield the final perception may well resemble the behaviour of the physical model. It could be that in some circumstances the link between disparity detection and conscious knowledge is more important for perception then the link

between retinal stimulation and disparity detection or indeed the dynamics of the response of disparity detectors. It would therefore be wrong to disregard the Julesz model because of neurophysiological findings on the primary functions of the visual cortex.

One of the features of the dipole model is the idea of a serial search for binocular disparities to give stereopsis. This might provide an explanation for the convergence-divergence asymmetry noted at the beginning of this chapter. As the observer awaits the stimulus the arrays of dipoles are locked together at zero binocular disparity. When the stimulus arrives each dipole changes to a new sign of polarity independent of its previously held one but with the possible exception of the area showing relative disparity the arrays are still locked together. If the relative disparity is not great this area may still remain locked in and thus will yield information on whether the relative disparity is convergent or divergent. If however, the relative disparity is very great, lock-in will not be possible initially. In this situation the two arrays must move across each to reduce the disparity of the special area in order to lock the dipoles in this region firmly together. This movement of the arrays may be performed by vergence movements of the eyes or as Julesz suggests by some form of cortical shifting mechanism. When the disparity between corresponding aggregates of dipoles is so great that there exists no clue as to whether the disparity is convergent or divergent, the shifting mechanism must move in one direction and presumably only return to investigate the other direction when the rest of the dipoles, originally firmly locked together, begin to break apart. The initial direction in which the arrays slide over each other may be determined by some chance decision or alternatively according to some constant preference. The results of Experiment 3 may now be considered in terms of this model. The square area

in the centre of the visual field undergoes a step change in binocular disparity but if the change in disparity is small then the arrays remain locked together everywhere and perfect stereopsis is obtained. If the disparity is large then the arrays must move and, if they are unable to do so in the time allowed, steropsis will not be possible. Furthermore, if there is always a preference or priority for convergent disparities being investigated first then large convergent disparities will be fused quicker than large divergent disparities. This could explain the convergent-divergent asymmetry found in Experiment 3. Experiments 10 and 11 may also be explained in this way. In Experiment 11 two squares, one 9 times the area of the other were used as stimuli in a random dot pattern at large convergent or divergent disparities. At this disparity of 20.4' of arc the large square was more likely to be correctly located in depth than the smaller square. In the dipole model the relative disparity that an aggregate of dipoles may possess before breakaway occurs depends upon the size of this area and particularly upon its dimension in the direction of shear. Thus, after the step change in disparity has occurred, the larger square may remain locked in but the smaller square may not. Similarly, in Experiment 11, it may be said that the greater success rate in depth localisation for the horizontally aligned rectangle is due to its greater tolerance to shear in the horizontal direction.

It is interesting to note that the feature of the dipole model which has been used here to explain the convergent-divergent asymmetry is the feature that Julesz found most inconsistent with his findings. He found that he could reverse the subjects natural preference for a convergent or divergent disparity when viewing an ambiguous stereogram by adding a little more evidence for one possible percept. He took this as an arguement against serial search procedure for binocular disparity which the dipole model

implies. However, since he used large regions of dots at small binocular disparity for his experiments it could equally well be argued that no searching was necessary anyway. If there were more dipoles present to give a convergent (divergent) disparity then the arrays would immediately lock-in to represent this convergent (divergent) disparity.

Although a certain amount of success has been had with Julesz's magnetic dipole model it cannot explain qualitatively the result of every experiment reported in this thesis. For example the drop in perceptual error rate as the stimulus is moved out of the centre of the visual field into the periphery (Experiments 7,8,9) finds no analogy in the dipole model. The asymmetry in stereoscopic ability between the left and the right hemisphere (Experiment 7) is not explained by the model as it stands. It is difficult to see how the model could ever be modified to deal with the implications of Experiment 12 which dealt eith interocular delay. Nevertheless it has shown to be a useful analogy in many other cases. The difficulties of obtaining stereopsis when only a small collection of dots in the two patterns show relative disparity are well illustrated by the Julesz model.

A bias in the initial direction of the search procedure may well explain how large convergent disparities are fused quicker than large divergent disparities but this does not explain the perception of an area in the random dot pattern of large divergent disparity prior to actual stereopsis. It is reasonable to assume that while the search procedure is underway (but proceeding in the wrong direction) the perception of such an area would be as if this area in one eye's view was filled with a pattern of dots different and independent to that which filled the corresponding area in the other eye's view. However, in an experiment designed to test perception in such a stiuation described in section 6.1 it was found that dots in

this area were located at various depths but all further from the observer than the reference plane. This experiment, performed first with a stationary noise pattern was repeated with dynamic noise and it was found that the dots remained in the reference plane but the area covered by the two independent noise sources could be easily detected from its texture. When the independent noise was added for only 80 milliseconds to what was originally a stationary picture the perception was similar to continuous viewing of a dynamic noise picture with a region made up from independent noise sources. If then an area in the random dot stereogram is suddenly given a large step change in disparity in a divergent direction, initial perception will indicate that this area is different from the rest of the dot pattern but its relative depth will be uncertain. This may explain the large error rate found in this situation in Experiment 3 but the author did not find that a brief exposure to an area of large divergent disparity appeared similar to a brief exposure to independent noise in each eye but this is only one subjective opinion.

Hysteresis is an important feature of the dipole model and it is a feature that may be invoked to discuss the experiments reported here. For reasons suggested above, a step change in disparity in the divergent direction may be perceived as a convergent disparity. Once this initial decision on depth has been made it could be that a much greater amount of evidence has to be produced to reverse the depth perception obtained. This would follow from any hysteretic model of decisions arising from conflicting evidence. As the duration of exposure or the size of stimulus increases the evidence for the opposite view builds up and gives correct perception. On the question of the time required to perceive a large divergent disparity as divergent, the results of Experiment 5 indicate that the error rate begins to decrease significantly at a duration of about 4 TV. frames or

160 milliseconds. This is the time required between stimulation of the retina and action by the eye muscles to perform vergence movements that change the point of fixation. It is therefore likely that such eye movements play a part in improving depth perception in this experiment. Hysteresis is a property that is exhibited by many mathematical models of the dynamics of large populations of neurons(WILSON&COWAN,1972)when inhibitory synaptic connections are included as well as excitatory. It is therefore reasonable to suggest that hysteresis may be a property of perceptual judgements.

Having made use of Julesz's magnetic dipole model of stereopsis and having found it only partially successful in explaining the experimental results obtained by the author, it is now necessary to consider these same results in the light of neurophysiological findings. Neurophysiological data are normally obtained from the cat which is an animal that possesses good stereopsis but there is a possibility that some of these findings are particular to the cat and do not apply either qualitatively or quantitatively to man. However, many such findings in the cat have been demonstrated by psychophysical experiments to be also true for man and it is therefore sensible to discuss results of perception experiments in these terms.

There are two possible explanations for the convergent-divergent asymmetry and its decline with peripheral angle. An investigation into the distribution of binocular disparity detectors in the visual cortex of cat (BARLOW et al, 1967) indicated (though not conclusively) that detectors of high disparity were more frequently found corresponding to peripheral regions in the retina than to the centre of the visual field. More detectors were found firing optimally for convergent disparities than for divergent disparities. It could be argued that the greater number of convergent disparities explain the convergent-divergent asymmetry but it is unlikely

that the distribution of disparity detectors as indicated by Barlow et al can explain the results of Experiments 7, 8 and 9. Taking Barlow's results as they stand, the gradual increase in the number of high disparity detectors as peripheral angle increases is more akin to the gradual change of width of Panum's fusional area with increase in peripheral angle than the author's results which show significantly large changes in error rate for a small (3^{o}) shift into the periphery.

The second explanation concerns the possibility of difficulties in stereopsis arising through the naso-temporal division in the retina. If there was perfect division of the visual field with no extra corrections made at the optic chiasm or through the corpus collosum then no stereopsis would be possible in the centre of vision. It has been suggested (BLAKEMORE, 1969) that a central strip of retina as wide as 1.5^{o} is represented in both cerebral hemispheres in man and evidence indicates (MITCHELL & BLAKEMORE, 1970) that this double representation in man is facilitated by a corpus collosal path. Although the naso-temporal division has been cited (FOX & BLAKE, 1973) for a failure of binocular summation of subliminal stimuli located on a vertical line through the fixation point it is not immediately clear how the author's experimental results may be explained. It is necessary to suggest that in this region of double representation detectors of large divergent disparities (of the order of 20' of arc) are not as frequent as detectors of equally large convergent disparities. With this extra hypothesis and Bishop's theory of tuned disparity detectors (BISHOP, 1970), it is possible to explain how a large divergent disparity may actually appear convergent to the observer. A stimulus of low binocular disparity (6' of arc) of either divergent or convergent direction makes a detector tuned to this disparity fire optimally whilst inhibiting those that are tuned to disparities close to the actual one shown. Detectors tuned

to far different disparities fire sub-optimally but are not inhibited. The optimal firing rate of one group of receptors provides the necessary information for stereopsis. A stimulus of high divergent binocular disparity provokes no optimal response from any set of detectors since there are none that are tuned to this particular disparity, but those detectors that do exist will fire at a rate dependent upon the difference between their tuned disparity and the divergent disparity presented. Those that respond to divergent disparities not too far from that presented will be inhibited whereas others that respond to convergent disparities will fire sub-obtimally at a rate higher than those that are inhibited. The information that the binocular disparity detectors now present to the brain is as follows. Over a great part of the visual field there is optimal firing rate of the zero disparity detectors but in the centre these detectors fire sub-optimally. There is no optimal response from any group of detectors in this region but there is a greater response per unit of the convergent disparity detectors then of the divergent disparity detectors as many of these latter are inhibited. Therefore the brain is able to identify the region in the centre by the lack of response at zero disparity and, because of the greater response per unit of the convergent disparity detectors, may come to the conclusion that the region in the centre of the visual field is in front of the rest of the dot patterns. This argument only holds for random dot stereograms because line drawing stimuli presented briefly outside Panum's fusional area, the region of patent stereopsis (OGLE , 1962), would yield double images. Information about whether these images are crossed (convergent disparity) or uncrossed (divergent disparity) would give a sense of further or nearer from the fixation point.

Experiment 12 was designed on the assumption that a corpus collosal path exists which enables a central strip of retina to be represented in

both cerebral hemispheres. The higher the binocular disparity of an object in the centre of the visual field, the more important this corpus collosal path is for stereopsis. The quite different effect of interocular delay on small and large convergent disparities indicated that in the problem of taking information from the two hemispheres for the one central area the left hemisphere may be given priority. Alternatively the results may be viewed as indicating that for objects in front of the fixation point there are more projections from the right hemisphere to the left than vice versa. The failure of divergent disparities to yield a similar result may be explained by the lack of high divergent disparity detectors in the centre of the visual field. Perception was poor at zero interocular delay and was not noticeably affected by its introduction.

The importance of Experiment 13 is that it demonstrates that masking a stimulus by binocularly presented noise with interocular delay leaves the stimulus less perceivable than if the stimulus in each eye was masked by a separate independent noise source. The reduction in stereoscopic threshold for the latter case over that obtained with each eye receiving an identical noise input is $1/\sqrt{2}$ and this fraction is also approached as the interocular delay becomes much greater than the stereoscopic summation time. It is apparent that this summation time does not adapt to interocular delay. This implies that the slowing down of the Pulfrich movement in dynamic random dot stereograms presented with interocular delay, is not due to a lowering of the cut-off frequency of low-pass filters in the human visual system. It is more likely that the apparent movement is derived from the interocular delay itself so that as this increases the apparent speed decreases. For reasons given in chapter 8, Experiment 13 cannot be seen as a good method for measuring the stereoscopic summation time. Nevertheless the value of 56 milliseconds obtained in this measurement

compares with the figure of about 50 milliseconds Julesz (JULESZ, 1971) found for his perception time for stereopsis (chapter 3). In addition, in experiments on binocular summation of subliminal stimuli (BATTERSBY & DEFABAUGH, 1969) it has been found that summation is possible for interocular delays of up to 50 milliseconds.

Experiment 13 was performed with very low visual signal to noise ratios. As mentioned at the end of chapter 8 an ordinary television picture may be sampled with different sampling points in each frame so that the effect is similar to a video signal degraded by impulse noise. If two sampled pictures are prepared for binocular viewing interocular delay may be placed between the sampling points of the two pictures by a small addition to the basic apparatus already described. This is shown in Appendix 3. When an ordinary television picture is sampled and binocularly viewed, the application of interocular delay produces the same Pulfrich effects described in chapter 8. An interocular delay of 1 or 2 frames smears out the impulse noise so that its effect is less irritating to the observer. When the interocular delay is exactly one frame or 40 milliseconds in length it is as if one frame of the degraded picture is first shown to one eye and then passed on to the next whilst another is shown to the first. From the results of Experiment 13 it would seem that the effective signal to noise ratio is increased without any change to the video signal. Therefore it should be possible to reduce the information in a video signal by sampling and then to reduce the ill effects of this process on perception by the use of interocular delay. However, any movement in the picture will be distorted by the Pulfrich effect and one would not expect to be able to improve the detectability of a fast moving stimulus by the application of interocular delay.

The author is of the opinion that more work can be done with the

apparatus described in this thesis to further characterise the dynamic nature of stereopsis. The process of stereopsis exhibits substantial inertia and hysteresis which should be revealed by experiments on movement sensitivity to stimuli in dynamic random dot stereograms.

A possible relation between eye dominance and the effects of interocular delay might be fully explored by using many more subjects than the author typically used in his experiments. These would be characterised according to eye dominance and their response to left eye and right eye delays measured. On the question of whether any part of the human visual system adapts to interocular delay this might be fully tested by using the methods of after-effects to overcome some of the disadvantages of Experiment 13. The subject would gaze for a time at a dynamic random dot stereogram presented with either a left or a right eye delay. After this his performance in visual tasks either monocular or binocular could be measured. By repeating this for various interocular delays it could be seen if the application of interocular delay caused any adaptation in the leading or lagging optic pathway or in the point of binocular fusion.

The effect of interocular delay on stereopsis from various sizes, positions and disparities of stimuli might be more fully investigated. Experiment 12 used only one size of stimulus, two disparities and only one magnitude of delay.

APPENDIX

A1. PROPERTIES OF PSEUDO-RANDOM SEQUENCES

A1.A INTRODUCTION

A pseudo-random sequence is a periodic sequence which exhibits over one cycle the properties associated with randomness.The sequence is generated according to some predetermined programme or mathematical algorithm.The algorithm is a difference equation and the algebraic operations are modulo-2 addition if a binary sequence is required.The difference equation may be modelled by a shift register with the state of the first stage of the register determined from a selection of later stages whose outputs provide the inputs of a network consisting of EXCLUSIVE-OR gates(modulo-2 adders).The pseudo-random sequence may then be looked upon as the natural response of a digital oscillator(HUFFMAN,1955).The length of the sequence depends upon the feedback arrangement but a maximum length is set by the order of the difference equation.

For certain feedback arrangements,sequences are obtained which over one period exhibit the run-length distribution expected of a random coin-tossing experiment.The autocorrelation function of the sequence is large at multiples of the sequence period and uniformly low elsewhere.The properties of pseudo-random sequences have been comprehensively studied (GOLOMB et al,1964) but their chief properties which are relevant to this thesis are set out in this Appendix.

A1.B LENGTH OF SEQUENCE

Fig A1.1 shows an N stage shift register where the first stage's input is the output ofthe feedback network.The N binary outputs of the shift register describe the state of the network.After the next clock pulse the pattern of digits moves one place to the right and the first stage X_1 becomes X_0 the previous output of the feedback network.Since

the feedback contains only modulo-2 adders and therefore is memoryless, the state of the network in the time interval k determines the state in the time interval k+1.Therefore,when the shift register contains a pattern it has previously held,a cycle is completed.In an N stage binary shift register each stage may have one of two values.Therefore there are 2^N possible patterns of N digits which the shift register may contain. However the all-zero state with a feedback network of modulo-2 adders would be self-perpetuating.The maximum length of sequence for an N stage shift register is then 2^N-1.A sequence which is of maximum length is called an m-sequence.

A1.C THE SHIFT AND ADD PROPERTY

A sequence from a generator which does not produce m-sequences is determined by the initial state of the generator as well as the feedback configuration.If one sequence that is produced is less than the maximum length,then not all the 2^N-1 possible states of the shift register appear.If the shift register is initially given a state which did not appear in the previous sequence,then the generator may either pass into one of the states that did appear before,in which case the previous sequence is produced,or it may periodically pass through an entirely new set of states to yield a second sequence.

In an m-sequence generator,the register passes through all states and so any one of the 2^N-1 possible states may be taken as an initial state and the same m-sequence is always produced.The m-sequence depends only upon the feedback configuration and not on the initial state.This fact may be used to derive the "shift and add" property of m-sequences.

For an N stage shift register the generator feedback equation may be written as,

$$a_0 = a_n \oplus a_p \oplus a_q \oplus \ldots \ldots \oplus a_r \qquad (A1.1)$$

where there are taps on stages n,p,q....r and $\oplus$ represents the linear

operator of modulo-2 addition which operates on the binary values $a_n, a_p, a_q \ldots a_r$. With a shift of k digits where k is non-zero nor an integral multiple of the sequence length (A1.1) becomes

$$a_k = a_{n+k} \oplus a_{p+k} \oplus a_{q+k} \oplus \ldots \oplus a_{r+k} \qquad \text{(A1.2)}$$

Adding the sequence to its shifted version,

$$a_0 \oplus a_k = (a_n \oplus a_p \oplus \ldots \oplus a_r) \oplus (a_{n+k} \oplus a_{p+k} \oplus \ldots \oplus a_{r+k}) \qquad \text{(A1.3)}$$

and following from the properties of the linear operator $\oplus$ this becomes

$$a_0 \oplus a_k = (a_n \oplus a_{n+k}) \oplus (a_p \oplus a_{p+k}) \oplus \ldots \oplus (a_r \oplus a_{r+k}) \qquad \text{(A1.4)}$$

If $a_n \oplus a_{n+k} = a'_n$, then $a_p \oplus a_{p+k} = a'_p$ and so (A1.4) may be written as

$$a'_0 = a'_n \oplus a'_p \oplus a'_q \oplus \ldots \oplus a'_r \qquad \text{(A1.5)}$$

The same feedback arrangement is represented here as in (A1.1) and since this gives rise to an m-sequence, the sequence indicated by (A1.5) must also be this m-sequence. The result of "shifting and adding" is a phase-shifted version of the original sequence.

A1.D THE AUTOCORRELATION FUNCTION

To obtain the autocorrelation function the logical levels of 0 and 1 of the m-sequence A are given the values −1 and +1 respectively to make sequence B. In this transformation modulo-2 addition is equivalent to multiplication with a sign change. The autocorrelation coefficients of the sequence X are defined as

$$R_r = \sum_{i=1}^{i=L} b_i \times b_{i+r} \quad , \quad \text{where } L=2^N-1 \qquad \text{(A1.6)}$$

where $b_i \times b_{i+r} \equiv a_i \bar{\oplus} a_{i+r}$. From the "shift and add" property, $a_i \bar{\oplus} a_{i+r} = \bar{a}_{i+d} \equiv \bar{b}_{i+d}$ if r is non-zero nor an integral number of sequence periods. Then, substituting this into (A1.6)

$$R_r = \sum_{i=1}^{i=L} \bar{b}_{i+d} = -1 \qquad \text{(A1.7)}$$

The last result follows from the fact that the sequence A has one more 1 than 0 digit when the all-zero state of the shift register is dis-

allowed.When r is zero or an integral number of sequence periods

$$R_0 = R_{KL} = \sum_{i=1}^{i=L}(b_i)^2 = L = 2^N-1 \qquad (A1.8)$$

The normalised autocorrelation coefficients are therefore

$$\begin{aligned} R &= 1 \qquad |r| = 0,L,2L,\ldots \\ R &= -1/L \qquad \text{elsewhere} \end{aligned} \qquad (A1.9)$$

This result is for discrete time only.To obtain the autocorrelation function $R(\tau)$ for continuous time it is necessary to consider the shape of the pulses.A rectangular pulse of width δ gives a triangular $R(\tau)$ as shown in Fig(A1.2) which is for the case when δ is the p.r.g. clock period.

A1.E THE POWER SPECTRUM

The Wiener-Khintchine theorem relates the power spectrum of a signal to the Fourier transform of its autocorrelation function.The autocorrelation function of an m-sequence of length L and clock period δ is periodic at intervals of L .The harmonic repetition frequency is therefore $2\pi/L\delta$ rad/sec and because $R(\tau)$ is an even function only the Fourier cosine component need be considered.The one-sided power spectrum(all power in the positive frequency range) is

$$F(\omega) = \frac{4}{L\delta}\int_0^{L\delta/2} R(\tau)\cos\omega\tau\, d\tau \qquad (A1.10)$$

and substituting $R(\tau) = 1-\tau/\delta$ for $\tau \leq \delta$

$$F(\omega) = \frac{4}{L\delta}\int_0^{\delta}\left(1-\frac{\tau}{\delta}\right)\cos\omega\tau\, d\tau \qquad (A1.11)$$

when it is assumed that $1/L \ll 1$ so that the out-of-phase correlation in $R(\tau)$ may be ignored.After integration (A1.11) becomes

$$F(\omega) = \frac{2}{L}\left(\frac{\sin\omega\delta/2}{\omega\delta/2}\right)^2 \qquad (A1.12)$$

and this is plotted in Fig(A1.3).

If the width t of the rectangular pulse in the sequence is smaller than the p.r.g. clock period δ then the new envelope is given by,

$$F(\omega) = \frac{2}{L}\left(\frac{\sin\omega t/2}{\omega t/2}\right)^2 \qquad (A1.13)$$

The harmonic repetition frequency remains $2\pi/L\delta$ but the first node is at $2\pi/t$ and not $2\pi/\delta$ .Therefore by making the pulse width t much shorter than δ the frequency spectrum becomes progressively flatter at the lower frequencies.If the harmonic spacing $2\pi/N\delta$ is very much smaller than the cut-off frequency of a low-pass filter which operates on the pseudo-random sequence,and the cut-off frequency is much less than the frequency of the first node $2\pi/t$,then the noise may be considered as white for the purposes of the filtering operation.

FIG. A1.1 A BINARY PSEUDO-RANDOM SEQUENCE GENERATOR

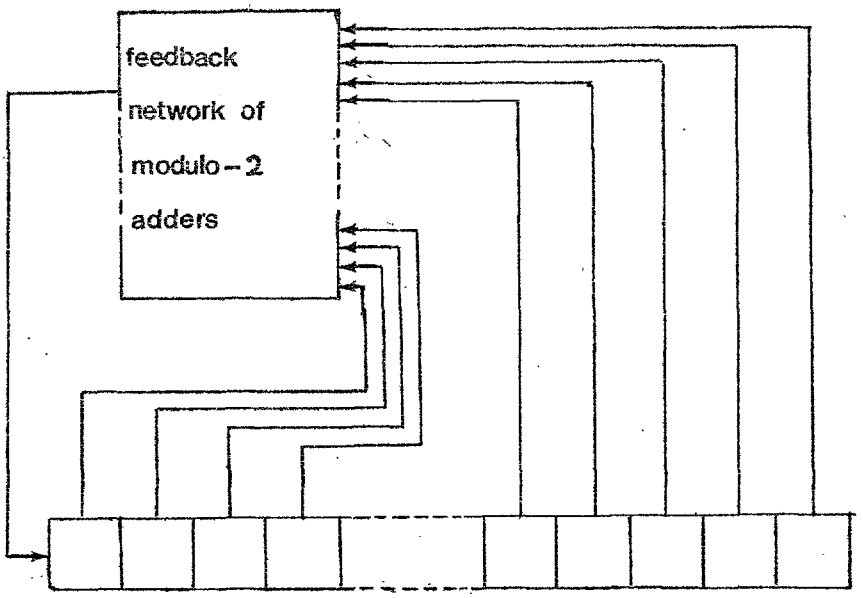


FIG.A1.2 NORMALISED AUTOCORRELATION FUNCTION OF BINARY M-SEQUENCE

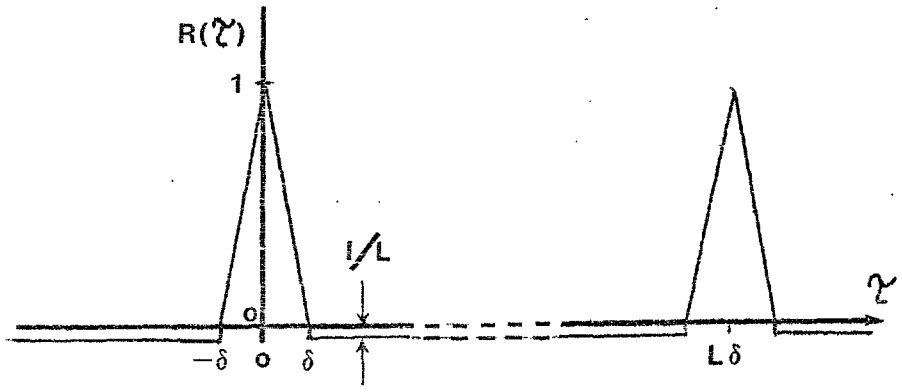
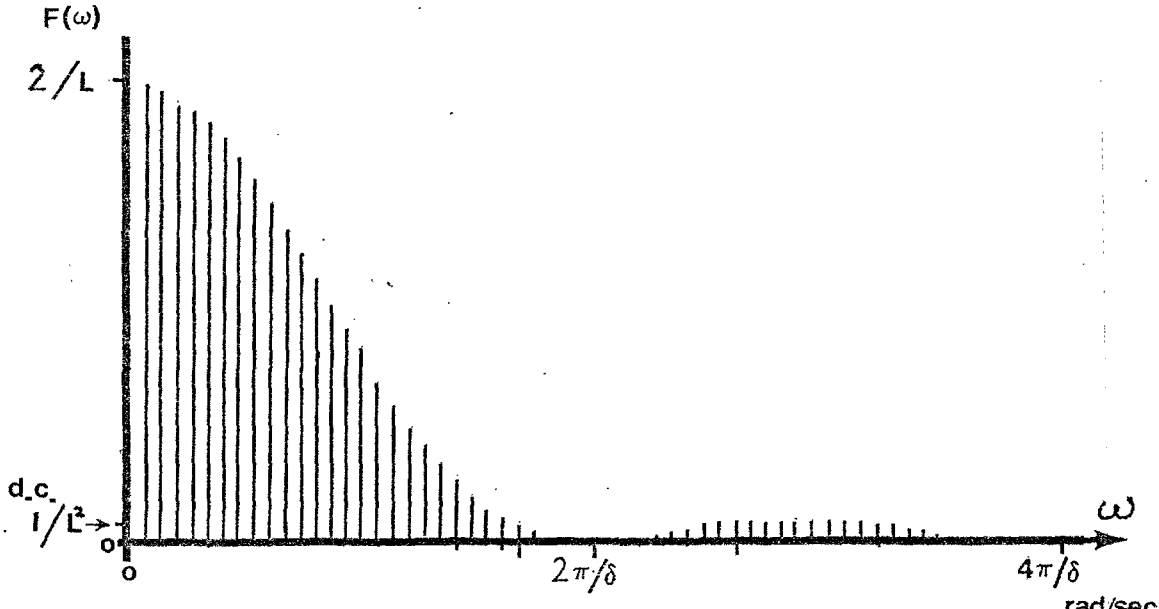


FIG.A1.3 POWER SPECTRUM OF M-SEQUENCE



Line spacing = $2\pi/L\delta$, δ = clock period

L = length of sequence

A2.-BINOCULAR CORRELATION AND INTEROCULAR DELAY

A2.A VARIANCE OF THE MEAN OF TWO VARIABLES WHEN A FINITE CORRELATION EXISTS BETWEEN THEM.

Consider a random variable X drawn from a population of mean $\bar{X}$ and variance σ_x^2. Consider also a variable Y, mean $\bar{Y}$ and variance σ_y^2. From X and Y a new variable $Z = (X+Y)/2$ is formed. Then

$$\bar{Z} = E(Z) = E((X+Y)/2) = (E(X)+E(Y))/2 = (\bar{X}+\bar{Y})/2 \qquad (A2.1)$$

and $$\sigma_z^2 = E(Z-\bar{Z})^2 = (E(X+Y-\bar{X}-\bar{Y})^2)/4$$

$$= \frac{1}{4}\left(E(X-\bar{X})^2 + E(Y-\bar{Y})^2 + 2E(X-\bar{X})(Y-\bar{Y}) \right) \qquad (A2.2)$$

The correlation coefficient ρ is defined as,

$$\rho = \frac{E(X-\bar{X})(Y-\bar{Y})}{\sqrt{E(X-\bar{X})^2 E(Y-\bar{Y})^2}} \qquad (A2.3)$$

and if $\sigma_x^2 = \sigma_y^2 = \sigma^2$ then

$$\sigma_z^2 = \frac{1}{4}\left(2\sigma^2 + 2\rho\sigma^2 \right) = \frac{\sigma^2}{2}(1+\rho) \qquad (A2.4)$$

A2.B LOW PASS FILTERING OF WHITE NOISE

Consider a filter with two time constants a and b. Its transfer function $H(j\omega)$ is given as,

$$H(j\omega) = \frac{1}{(1+j\omega a)(1+j\omega b)} \qquad (A2.5)$$

If the white noise is operated on by this filter the output power is proportional to

$$P_0 = \int_{-\infty}^{\infty} \left| H(j\omega) \right|^2 d\omega \qquad (A2.6)$$

$$= \frac{1}{a^2 b^2} \int_{-\infty}^{\infty} \frac{d\omega}{\left(\omega^2 + \frac{1}{a^2}\right)\left(\omega^2 + \frac{1}{b^2}\right)} \qquad (A2.7)$$

$$= \frac{1}{a^2 - b^2} \int_{-\infty}^{\infty} \left[\frac{1}{\omega^2 + \frac{1}{a^2}} - \frac{1}{\omega^2 + \frac{1}{b^2}} \right] d\omega \qquad (A2.8)$$

$$P_0 = \frac{\pi(a-b)}{a^2-b^2} = \frac{\pi}{a+b} \qquad (A2.9)$$

If the time constant a is kept constant but b takes on two values b_0 and b_1, then the ratio of the noise power for these two values of b is

$$\frac{\text{NOISE POWER WITH } b = b_1}{\text{NOISE POWER WITH } b = b_0} = \frac{a + b_0}{a + b_1} = \frac{1 + b_0/a}{1 + b_1/a} \qquad (A2.10)$$

A2.C CORRELATION COEFFICIENT AS A FUNCTION OF THE FILTER CHARACTERISTICS AND INTEROCULAR DELAY

The model the analysis is referred to is shown in Fig(8.5) and the symbols are as in the diagram. At the point of fusion the two signals $s_1(t)$ and $s_2(t)$ are related by the interocular delay T so that

$$s_2(t) = s_1(t-T) \qquad (A2.11)$$

Considering only the noise component of $s_1(t)$ and $s_2(t)$ the cross-correlation $\Phi_{12}(\tau)$ is

$$\Phi_{12}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} s_1(t)\, s_2(t-\tau)\, dt \qquad (A2.12)$$

$$= \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} s_1(t)\, s_1(t-T-\tau)\, dt = \Phi_{11}(T+\tau) \qquad (A2.13)$$

The signal $s_1(t)$ is related to the noise input n(t) by the filter impulse response h(t) in the following way,

$$s_1(t) = \int_{-\infty}^{\infty} h(u)\, n(t-u)\, du \qquad (A2.14)$$

so that the substitution of (A2.14) into (A2.13) gives

$$\Phi_{11}(T+\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} \left[\int_{-\infty}^{\infty} h(\lambda) n(t-\lambda) d\lambda \int_{-\infty}^{\infty} h(u) n(t-u-T-\tau) du \right] dt \qquad (A2.15)$$

and after interchanging the integrals this becomes

$$\Phi_{11}(T+\tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(\lambda)h(u)\, du\, d\lambda \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} n(t-\lambda)n(t-T-u-\tau)\, dt \qquad (A2.16)$$

From the properties of the autocorrelation function of noise the last integral becomes the δ function and (A2.16) simplifies to,

$$\Phi_{11}(T+\tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(\lambda)h(u)\, \delta(\lambda-u-T-\tau)\, d\lambda\, du \qquad (A2.17)$$

Performing one integration (A2.17) becomes

$$\Phi_{11}(T+\gamma) = \int_{-\infty}^{\infty} h(\lambda)\, h(\lambda - T - \gamma)\, d\lambda \qquad (A2.18)$$

The term on the right is the autocorrelation function for the impulse response h(t).The correlation coefficient of interest is

$$\Phi_{12}(0) = \Phi_{11}(T) = \Phi_{hh}(T) \qquad (A2.19)$$

From the Wiener-Khintchine theorem $\Phi_{hh}(T)$ is related to $H(j\omega)$, the filter transfer function.

$$\Phi_{12}(0) = \Phi_{hh}(T) = \int_{-\infty}^{\infty} \left|H(j\omega)\right|^2 \exp j\omega T \, \frac{d\omega}{2\pi} \qquad (A2.20)$$

For the filter shown in Fig(8.5),

$$\left|H(j\omega)\right|^2 = \frac{1}{a^2b^2(\omega - j/a)(\omega + j/a)(\omega - j/b)(\omega + j/b)} \qquad (A2.21)$$

The integral in (A2.20) is evaluated by the method of residues.Considering $\omega = u + jv$,a complex number, the contour of integration is taken along the real axis u and around the positive imaginary half of the complex plane.Summing the residues at $\omega = +j/a, +j/b$ the integral becomes

$$\Phi_{12}(0) = \frac{be^{-T/b} - ae^{-T/a}}{2(b^2 - a^2)} \qquad (A2.22)$$

This correlation coefficient may be normalised giving,

$$\phi_{12}(0) = \frac{be^{-T/b} - ae^{-T/a}}{b - a} \qquad (A2.23)$$

This formula does not hold for b = a because if this occurs the filter has a double pole and the residues calculated for single poles at $+j/a, +j/b$ are not correct.The formula for this case may be found by writing $b = a + \epsilon$ and considering the limit as $\epsilon \to 0$.

$$\phi_{12}(0) = \lim_{\epsilon \to 0} \frac{(a+\epsilon)\, e^{-T/(a+\epsilon)} - ae^{-T/a}}{\epsilon}$$

$$= e^{-T/a} + \lim_{\epsilon \to 0} \frac{ae^{-T/a}\left(e^{-T\epsilon/(a(a+\epsilon))} - 1\right)}{\epsilon}$$

$$= e^{-T/a} + ae^{-T/a} \lim_{\epsilon \to 0} \frac{\left(1 - T\epsilon/a^2 + T^2\epsilon^2/2a^4 - \ldots\ldots - 1\right)}{\epsilon}$$

$$= e^{-T/a}\left(1 - T/a\right) \qquad (A2.25)$$

A3. A VIDEO SAMPLING SYSTEM WITH INTEROCULAR DELAY

Fig(A3.1) demonstrates the system used. Taps are taken from one pseudo-random sequence generator at stages 8,11,15 and 23 to provide a four bit binary number.This is compared to another four bit number selected by the experimenter.If it is greater than the fixed number, the output of the comparator is high and closes the video switch allowing the video signal from the camera into the monitor.By varying the input to the comparator the density of sampling points may be varied.Another pseudo-random sequence out of phase with the first governs the video input to another monitor.In this way an ordinary television picture may be binocularly viewed with sampling points in the two sources identical except for an interocular delay.If only one camera is used the interocular delay must be an integral number of television frames.Plates A3.1,2 show sampled television pictures.

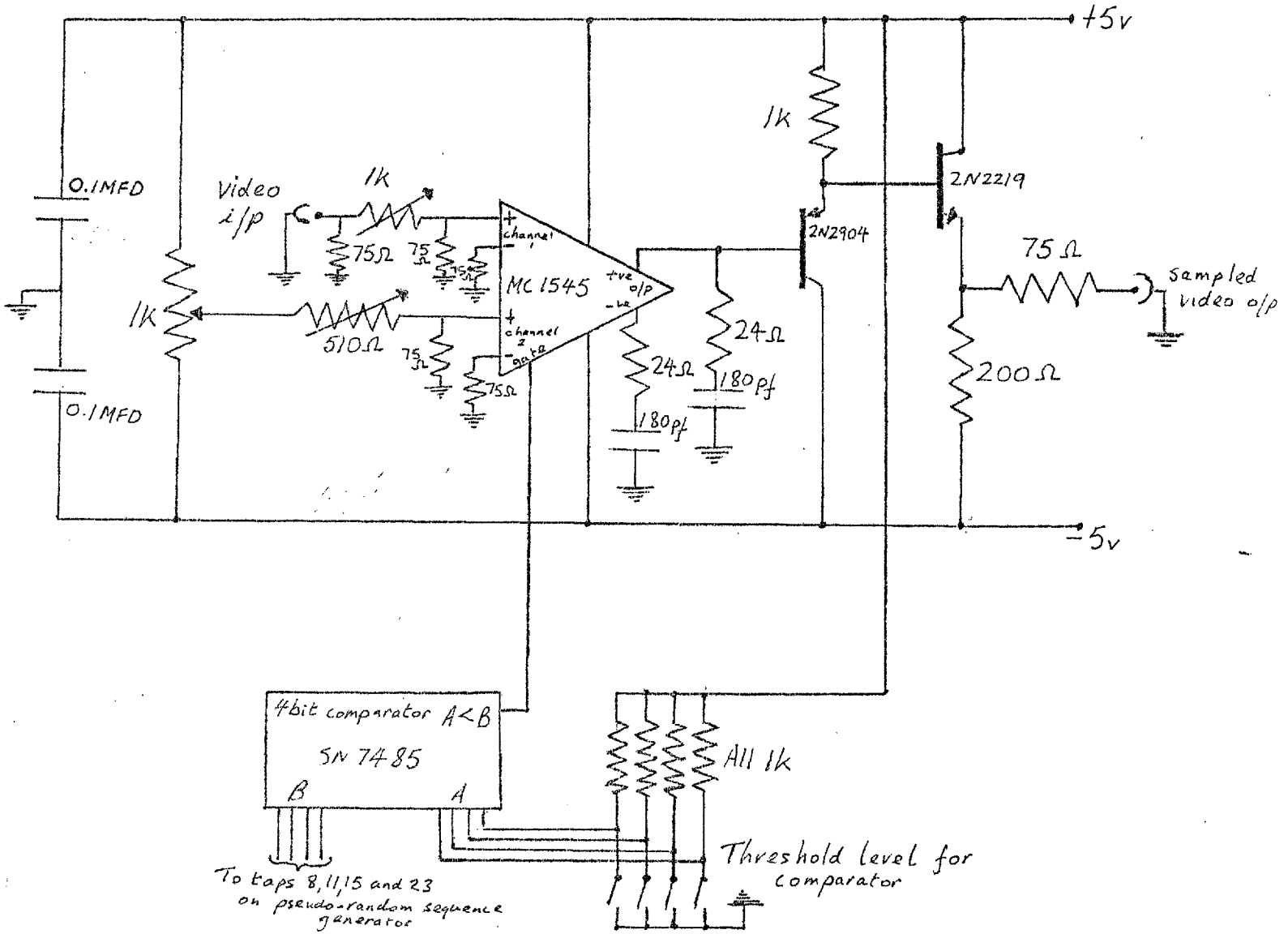
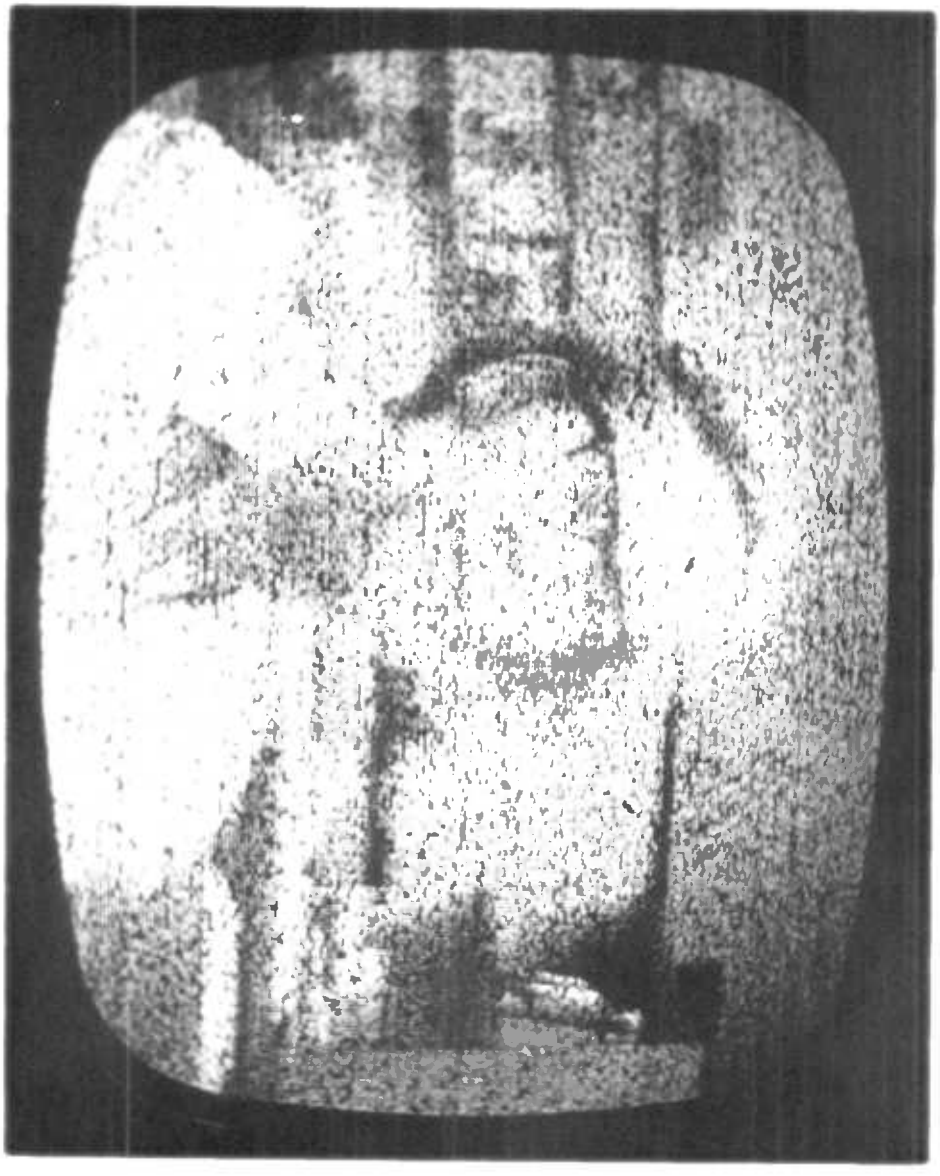


FIG. A3.1 VIDEO SAMPLING CIRCUIT

PLATE A3.I A SAMPLED TELEVISION PICTURE



PLATE A3.2 A SAMPLED TELEVISION PICTURE



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