A COMPUTER MODEL

of

INFANT PERCEPTUAL DEVELOPMENT

BY

PETER BRUCE WILLATTS

Abstract

A theory is presented of the development of pattern recognition and looking behaviour in infancy. It is proposed that scanning habits are acquired and patterns recognized with the reproduction of fixations and eye movements in the order in which they originally occurred. Recognition is achieved by correctly predicting the current input for each fixation. Evidence supporting this proposal is discussed, and the limitations of other theories are examined. A case is made for the storage of two kinds of visual information, originating from central and peripheral vision respectively.

Infants indicate recognition of familiar patterns by looking less at them than patterns which are new. This can be explained by the discrepancy principle which proposes a curvilinear relation between the amount of looking and degree of discrepancy between a pattern and its representation in memory. This principle is incorporated in the theory to account for the control of the length of sequences of fixations.

A computer model of the theory is described. This contains a simulation of the cortical processing of visual input, a number of oculomotor reflexes, learning mechanisms, and the means of controlling the length of a fixation sequence by assessing its discrepancy with the contents.

of memory. The model was run on a computer and learned to recognize patterns by scanning them and reproducing the original sequences of fixations.

The ability of the model to mimic infant looking behaviour is shown in three simulations of different infant experiments. Recognition was demonstrated by a decline in looking at familiar relative to new patterns, and this ability was retained after a delay. Such behaviour took time to develop, and the model required a certain level of visual experience before it appeared. Individual differences in the performance of the model resembling tempo differences in infants were also produced.

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CHAPTER 1.

THE ROLE OF EYE MOVEMENTS IN VISUAL PERCEPTION.

1. Introduction.

There is a basic puzzle about visual perception which concerns the striking difference between what we see and experience and the way we carry out our looking. The world we see has a wholeness and clarity in every part. When we walk into a room we seem to perceive the room in its entirety the moment we go through the door. Even though we may focus attention on one part of the room, we are still aware of the remainder, and the completeness of our perception is retained.

This experience contrasts with what is known about the structure of eyes and the way they are used for looking. The fovea, which is the only area capable of detailed vision, is 1/1000th. of the total retina. This means that to gain more than a 'keyhole' glimpse of the world the eye must be moved about to achieve a maximum of coverage. While one glimpse supplies only a limited view, a succession of different glimpses will fill in the picture.

While an eye movement is being made, it appears that vision is depressed (Volkmann, 1962, Zuber & Stark, 1966), and whatever might be registered is likely to be blurred as the velocity of even a small saccade can reach 450 degrees per second (Yarbus, 1967). This suggests that the input to the visual system typically occurs in a series of bursts or discrete packages, each separated by a short interval of time and originating from a different region of the surroundings (Gaarder, 1968).

The discrepancy between this description of visual input and actual visual experience is the starting point of this thesis. The physical structure of the retina permits only a tiny part of a scene to be viewed clearly at any time, and the nature of eye movements must be considered in an explanation of perception. Because of the smallness of the fovea, it is essential that eye movements be organized. Random scanning is not an adequate strategy for there would be little chance that the same regions would be fixated when stimuli were seen again, and recognition would be severely hampered. Exhaustive scanning of the whole stimulus field would not be a suitable alternative, for although it would be certain that nothing had been missed, the time required for such a scan would be prohibitive.

Visual exploration may be likened to the examination of a scene with a telescope. The difficulty here is the accurate positioning of the telescope, but the problem can be solved if a record is kept of all the movements which are made. This may then be used as a program of control to direct scanning on a subsequent occasion. For example, the program for looking at a house might be 'when the door is seen, move the telescope 10 degrees left and 5 degrees up to find the window, then move 20 degrees right and 15 degrees up to find the edge of the roof etc.', With such a program, a series of looks through the telescope will quickly and efficiently reveal the necessary parts of the scene.

This example shares in common with other sequential tasks the idea of a controlling plan or schema. This concept has proved extremely useful in explaining how sequences of behaviour are organised, particularly when any one of a number of different actions is possible at any stage of the sequence (Miller et al., 1960, Lashley, 1951). It will be argued that for eye movements there are controlling schemata which govern the ordering and positioning of fixations during pattern recognition. While it is accepted that the control of visual exploration is important in many other situations, for example problem solving and guiding actions, the recognition of patterns was chosen because this ability is fundamental to most other behaviour, and is one of the first to appear in the repertoire of the infant.

It should be stressed at this stage that while a great deal of visual perception depends on scanning, this is not to deny the possibility of perception when eye movements are limited or ruled out completely. The evidence of the tachistoscope testifies to this fact, but we are concerned here with how a series of 'tachistoscopic' views are organized. Recognition of complex displays is quite possible with exposures too brief to permit eye movements (Mooney, 1958), but in normal viewing people prefer to make a series of fixations. This certainly improves recognition since the more fixations a picture receives during the learning phase, the more likely it is to be recognized (Loftus, 1972). We may agree with Luborsky et al. (1963) that while the tachistoscope can give us information about perception during a fixation, a great deal more will be obtained when the scanning of normal vision is permitted.

If eye movements during the recognition of a pattern are controlled by a schema, the exact nature of this control must be specified. Chapter 2 will be devoted to this, and a theory which emphasises the contribution eye movement information makes within a schema will be put forward. One of the main arguments of this thesis is that a schema representing a pattern contains two sorts of information. The first is derived from central vision and consists of the several pattern features which are detected during a fixation on one region of a pattern. The second is derived from peripheral vision which specifies the target for the next fixation, the target which an eye movement will bring to foveal vision.

It should be noted that an explanation of the control of eye movements in terms of a schema merely begs the question of how the schema is established in the first place and what controls exist prior to the establishment. This consideration necessarily requires a theory to provide an explanation of schema development, and this is also discussed in chapter 2. The developmental aspect is continued into chapter 3 where mechanisms which control the amount of attention given to patterns are examined. These mechanisms depend on the types of schemata which are constructed and the patterns which are seen, and operate at all stages of schema building and use.

The remainder of the thesis will describe a computer simulation of the theory elaborated in the first 3 chapters. Following the description of the model, there are chapters showing the model in operation, and an evaluation of the simulation by a comparison of its behaviour with that of infants in a number of different experimental settings.

The rest of this chapter will amplify the points made above concerning the nature of scanning behaviour, the role of the schema and the conclusions which may be drawn, about the part played by eye movements in pattern learning the recognition.

2. Eye Movements and the perception of complex objects.

The way people look at complex scenes such as pictures has only recently been studied, partly because of the lack of adequate theories to explain the phenomena and direct research, and partly because of the lack of suitable recording equipment which would allow the use of stimuli more complex than a single point of light. Undoubtedly the ingenious inventions of Yarbus in Russia and Mackworth in America have provided an impetus for research.

Yarbus (1967) invented an extremely accurate method of recording the movements of a subject's eye while viewing pictures. A small mirror is attached to the surface of the cornea with a suction cap, and a sharp beam of light is reflected onto a sheet of light sensitive paper. Any movement of the eye is recorded as a displacement of the reflected beam on the paper, provided the subject's head is immobilised.

Yarbus showed his subjects a variety of pictures for 2 to 3 minutes with the instructions simply 'to look at the pictures'. The records demonstrate several interesting points, though no attempt is made to quantify the data. The most noticeable feature is that the subjects only examined certain parts of the pictures. Of these, some are looked at much more frequently than others. Yarbus suggests that it is only parts which contain information essential for perception which are fixated. Areas lacking detail are rarely looked at, and regions of contour and edges receive most attention. However, the presence of detail does not automatically lead to fixation and there is evidence of considerable selection.

This selection is interpreted as the subjects' attempts at understanding the pictures. In a woodland scene it is mainly the bears in the centre and the fallen logs around them which are picked out. The face of a girl shows a few looks at the outline of the head and the majority concentrated on the eyes, nose and mouth, a finding which has been reported elsewhere (Sakano, 1963). In no case was it observed that the contours had been closely followed except for one picture of the profile of a head in which most detail was found at the edges.

Yarbus conducted an interesting experiment which involved showing the same picture and asking a variety of questions about it. The fixation records showed that the distribution of looks depended on the question asked. A request to give the ages of the people pictured in a room restricted viewing completely to their faces; a question about the material circumstances of the family produced examination of their faces, clothes and furniture as well.

Many of the records Yarbus reproduces of the 'simple looking' show both the points of fixation and the pathways followed by the eye as it moved. Not only are certain regions examined in detail, but the same movements of the eye tend to be repeated to the extent that parts of the record become heavily overlaid. Yarbus detected the formation of cycles of fixations in many records, and it was clearly demonstrated in 2 records taken from the same picture for periods of 2 and 30 minutes of viewing. In the longer record there are far more fixations and movements, but the same repetitive patterning is evident in both.

Mackworth and Morandi (1967) made similar observations with subjects also looking at pictures. Records were made with the Mackworth Stand Camera (Mackworth, 1967) which reflects a small beam of light from the surface of the cornea onto photographic paper. This paper is previously exposed to the picture which is seen so that an immediate record of fixations may be obtained. The cornea has a centre of rotation different from that of the eye itself so that a rotation of the eye changes the position of the reflected beam.

The records again showed that only certain regions are fixated and others completely ignored. In order to determine the characteristics of fixated regions, a value of the informativeness of different parts of the pictures was obtained. Each picture was cut into 64 squares and judges rated each for the ease with which it could be recognized. This revealed that areas judged more informative received many more fixations that those which were less informative. Generally such regions contained some contour while areas of texture were ignored.

The informativeness value of each fixation was obtained, and the sum for each 2 second period of the 10 second trials determined. These scores showed that no one period contained more informative looks than any other. The very first fixations were as informative as the last which suggests that subjects are able to assess rapidly which areas are worth their attention.

Baker and Loeb (1973) also showed the influence on fixation patterns of high information regions in randomly generated shapes. Three types of shape were used, 4 sided polygons, histogram figures and computer generated shapes of loops, curves, angles and straight lines. For the polygons, the corners attracted most looks with the uppermost corner being examined the longest. The histograms were fixated most at the top (since this was where the figures differed), and especially where the heights of the columns changed. The computer generated forms were looked at most at the top as well, though the two lower corners also attracted some fixations.

It is not clear why the tops of such figures attracted more looks, but Gould and Schaffer (1965) also reported this effect for matrices of 36 digits. It is apparent that the regions receiving most attention are those which are typically counted high in information value, and this was supported by good correlations between subjects' ratings of the most important parts of the figures for recognition and the distribution of fixations.

These studies show that the distribution of attention is highly selective when viewing pictures in relatively unstructured situations in which all the subject seems to be doing is indentifying what is depicted. It would appear from Yarbus' studies that quite specific instructions must be given in order to significantly alter the normal pattern of looking. This normal pattern consists of fixating those regions which contain detail and contour, and which are classed as informative and important in distinguishing the picture so that it may be recognised.

Thomas (1968) has extended the range of these studies to record visual exploration in real-life situations. This is achieved with a device which superimposes the reflected beam from the subject's cornea onto a film recording of the scene being viewed. The apparatus is worn on the head, and though restricting vision through one eye, provides information about fixations while the subject is moving.

Recordings were made while the subject was driving a car, and again only specific items were inspected. The edges of other vehicles, road signs and flashing lights were all frequent targets. Novel and unexpected objects were particularly attractive, and it would seem that drivers will ignore much of the scene which is unimportant regarding driving, but maintain a state of readiness for anything which may become relevant. Despite the qualitative analysis, this study indicates that viewing the real world and pictures both show the same tendencies.

3. The Central Organization of Eye movements.

When a subject looks at a picture the location of his fixations is not a random affair. A frequent conclusion is that regions which provide information are those which are selected for fixation, but we need to explain what decides whether a region is informative. There would seem to be two possibilities here. One is that the visual system is especially sensitive to contour and changes along a contour such as corners. These are detected peripherally and lead to a fixation, the eye being 'drawn' around the scene. Recognition in this situation would be rather a passive affair, since the choice of where to look depends on the nature of the picture. If recognition is the process of matching a stored representation of a picture with what is seen it will be at the mercy of the picture and the way it is presented. Quite small changes to the contours of the picture or in the background against which it is presented could disrupt the location of fixations and prevent recognition.

The alternative would be to let the representation control the looking itself so that regions which are informative depend on what the observer thinks he is seeing. Recognition in this situation would involve directing the fixations from 'within' rather than letting them be guided from the outside, a process which has been described as 'perceptual attack' (Mackworth and Otto, 1970). It will be recalled that Yarbus asked his subjects various questions about the same picture and obtained different patterns of scanning depending on what information was required. The assumption that the nature of the picture alone determines looking is unable to explain these findings.

If the schema for a pattern consists of a number of distinctive features, the purpose of a fixation would be to locate and identify these features, an idea which is supported by an experiment conducted by Loftus (1972). Subjects were shown a series of 180 patterns, presented in pairs for trials of 3 seconds. The subject could choose how to divide her attention, and eye movements during the inspection were filmed. A recognition task was given in which the original 180 pictures were shown with 180 new ones, and the subject had to indicate whether a picture had been seen before with a yes/no answer.

It was found that the probability of correctly identifying a picture as one that had been seen before correlated directly with the number of fixations the picture had received during inspection. This suggests that the more fixations there are, the better the chance that some distinctive feature will be located. Loftus tested this idea by asking his subjects whether there was some such feature with which they made their judgement and examining the records to see whether this had been fixated. It was found that the probability was 0.95 that this feature was looked at by the third fixation.

Although this result indicates that fixations serve to isolate distinctive features, the task could not be described as pattern recognition since the subjects were clearly not responding to the pictures as a whole. What is needed is a situation where subjects have sufficient time to scan a picture and construct a more detailed schema. Mackworth and Bruner (1970) studied the effects of this with adults and 6 year old children. Two series of pictures were used consisting of colour prints with 3 degrees of blurring. Each picture was presented as sharp, blurred or very blurred in one series (inspection) or in the reversed order (recognition), and was shown twice for a 10 second exposure.

This design is interesting if the status of the very blurred picture is considered for each group. When the inspection group of subjects sees this picture they know what it represents from their experience with the sharp and blurred versions. The recognition group, on the other hand, are confronted with the very blurred picture on the first trial, and their looking might be expected to differ because of this lack of knowledge.

The recognition group showed longer fixation times when looking at the very blurred picture, which could be due to the difficulty in identifying the region fixated or in choosing the target for the next fixation or a combination of both. When eye movements were made, their direction depended on whether the subject knew the identity of the picture. In the sharp focus presentations the majority were along a horizontal axis, but for the blurred pictures, before they were recognized, eye movements tended to follow the vertical extent of the display. As soon as an identification had been made, the horizontal direction was preferred. It is interesting that only the adults showed this distinction depending on whether the picture was known or not. Children also scanned more in a horizontal direction, but equally for both conditions.

The informativeness of each fixation was obtained by judges as in the Mackworth and Morandi study, and the recognition trials showed that adults fixated areas which contained more information than those fixated during the inspection. This suggests that the schema constructed from a sharp display contains more component features than one generated from a very blurred picture. The blurred picture has fewer informative areas, but these are the ones which are fixated, hence the high rating per fixation.

The sharp picture has many more informative regions so that scanning is more wide ranging. When this pattern of scanning is applied to the blurred picture, more low-information regions are looked at and the mean rating per fixation is lower. This interpretation is supported by an analysis of the distribution of fixations which shows a greater tendency to cluster on restricted areas for the very blurred picture in the recognition series.

Although the differences which were found in the direction of scanning are difficult to interpret, the distribution of fixations under the two conditions suggests the influence of a schema. The experience with the sharp picture establishes a schema which produces the wide ranging scanning when the blurred versions are seen later. When these blurred pictures are seen first, there is no such prior experience and the pattern of looking is different.

The distinction between these two stages in the formation and use of a schema was made elsewhere by Zinchenko et al. (1963) The authors argued that perception and recognition may be separated to some extent, and both may follow different courses of development. Perception is an act which results in the formation of a schema('image' is the term Russian authors prefer to use), while recognition is an act of comparing a stimulus with a schema stored in memory.

These two processes were studied with children ranging from 3 to 6 years of age. The formation of a schema was explored by showing simple outline shapes and asking the children to simply look at them for 20 seconds. Eye movements were recorded by filming with a camera mounted in the centre of the stimulus display. The records showed that 3 year olds were capable of forming only limited representations of the shapes as their fixations tended to cluster about one point, particularly the circular lens of the camera. The intermediate children showed similar clusterings, though on the borders of the shapes, and the 6 year olds exhibited the best exploration by covering a wider area and making far more eye movements.

The assertion that these various patterns of scanning corresponded with different types of schemata was tested by showing the inspection shapes later among others which had not been seen. The distinction between perception and recognition was borne out since the 3 year olds explored the shapes more fully when given this specific task. Despite this improvement, they failed to recognise many figures, and even when successful were much slower than the other children. Their inability to examine the shapes fully in the inspection trial resulted in a schema which was inadequate for the recognition task.

The older children were much better at recognition, correctly identifying the shapes with faster times and an economy of fixations. The key features were recorded in the schema and a few brief looks sufficed to identify the shape and where necessary, discriminate it from others.

A further experiment was conducted to explore the scope of the perceptual schema. The children were asked to sit in front of a blank screen and imagine the shapes they had been viewing. The eye movements recorded during this exercise bore a close resemblance to those appearing during the inspection phase. The 3 year olds produced the clustering of fixations, while the 6 year olds showed an extensive tracing of the imagined outlines. This result is interesting not only because it shows how different schemata produce different patterns of eye movements, but also because it implicates an important motor component in the structure of a schema. In addition to containing the pattern features which fixations isolate, the schema has the capability of initiating and directing eye movements during the matching process of recognition.

A similar conclusion was reached by Leontyev and Gippenreiter (1966) who showed that even when subjects were instructed to supress all eye movements while identifying material surrounding the fixation point, reduced saccades of up to 2 degrees continually appeared. A further experiment involving the tachistoscopic presentation of characters either to the left or right of the fixation point resulted in postexposural eye movements in the same direction as the initial stimulus had appeared. A similar effect was reported by Mandes (1970) who found that when the post-exposural eye movements were in the direction that the non-identifying end of a stimulus had occupied, errors in identification were likely to occur.

4. CONCLUSIONS: The Role of Eye Movements in pattern recognition.

These various studies permit several conclusions to be drawn concerning the involvement of eye movements in the learning and recognition of patterns. Whenever a pattern has a larger angular size than the fovea, a series of fixations on different regions must be made. These are concerned with detecting important features which identify the pattern and reveal its structure, and typically are located where there is contour and contrast. Committing a pattern to memory requires that these features be recorded in a schema, and this process will include spatial information as well. Not only is information concerning the features recorded, but also their arrangement and hence the means by which they may be located again.

This is an important aspect of memory since it is no use just to record material without specifying how it may be retrieved; a library without an index is a nightmare.

Since visual recognition is an active process, retrieval becomes a matter of specifying where in the visual field the features may be found. It will be recalled that Yarbus showed fixations on faces were restricted mainly to the eyes and mouth despite considerable differences in the kinds of face and in the alternative contours which were present in the pictures. Eye movements are ballistic and require that a target be specified before the movement is made. Once initiated, no corrections to the movement may be made until it is completed (Robinson, 1968). Despite this restriction only specific facial features were fixated, and the conclusion must be that subjects know exactly what to look for and where to find it.

Eye movements serve two functions depending on whether a pattern is being learned or recognized. During learning features are picked up from different regions, and the scanning may be controlled by existing schemata, or where none are appropriate by the pattern itself. The outcome is a schema for the pattern which in turn will serve to organize looking when recognition is to be achieved. In this situation eye movements are made to detect whether specific features are present, rather than to find out just what features might be there.

CHAPTER 2.

A THEORY OF EYE MOVEMENTS AND PATTERN RECOGNITION.

1. Introduction.

The matching of a schema with a pattern reveals that eye movements have a critical part to play, for only by changing the position of the fovea will enough detail be seen. This requires a considerable degree of accuracy as the fovea covers only a small area and the visual world is large and contains many competing areas of interest. A schema has a dual role and must function as a record of pattern features and as a 'motor program' which can control the search for these features.

This suggests that there will be two kinds of information contained within a schema. One will derive from the feature processing carried out during a fixation, and the other will record the eye movements necessary for scanning. In this chapter the evidence from the literature will be considered that visual information is of these two types, and further that each is processed by a different system.

If this distinction exists it becomes necessary to explain how these components are combined within a schema. There are several existing theories (Hebb, Noton and Stark and Didday and Arbib) concerned with this problem, and each will be discussed and examined. There are difficulties with all of these theories, and following a critical examination and discussion of relevant literature a different approach will be put forward.

2. Hebb's theory of Cell Assemblies and Eye Movements.

This is an early, speculative theory which involved eye movements although Hebb was concerned with wider issues, in particular the relationship between a stimulus and a response (Hebb, 1949). The theory was expressed in neurophysiological terms, and its strength lay in the relatively clear and unambiguous terms which such an expression involved.

Hebb chose vision as the sensory system with which to elaborate his theory and the obvious candidates for response mechanisms were eye movements. While accepting the Gestalt proposals that perception was of wholes which could be independent of the constituent parts, Hebb determined to show how such wholes could be constructed from separate components. These were assumed to be small portions of object contour such as lines and angles. This idea was based on the reports of patients recovering from blindness (von Senden, 1960), various experiments on rat's abilities in visual discrimination tasks and the (then) current evidence for contour detectors in the visual cortex (Marshall and Talbot, 1942). Later work has confirmed that the initial stages of visual processing do involve a breakdown of contours into such basic features (Hubel and Wiesel, 1962).

When a part of an object is fixated, simple features are detected and result in a certain assembly of cells becoming active. An eye movement, the motor response, then shifts the point of fixation to another location and a new assembly becomes active. This eye movement will also be represented by an assembly of active neurones, and there is no essential difference between these two kinds of assembly except one results from sensory and the other from motor processes.

Learning occurs by linking assemblies together with the growth of neural dendrites, the only requirement being that assemblies are activated repeatedly and in quick succession. A sequence of fixations and eye movements around a pattern will result in a sequence of assemblies, each corresponding to the visual inputs and eye movements linking them in alternation. These phase-sequences have the property that activation of only a few constituent cell assemblies will activate the remainder by means of the connections which contiguity has established. With this process Hebb accounted for the perception of a whole pattern even though only a few parts are examined.

This conception of the phase sequence explains why the 'Interruptions' of eye movements do not disrupt perception. Just as the 'spatial' blind spot in the retina becomes filled in, so with the 'temporal' blind spot there is a filling in due to the activation of the whole phase sequence. In addition, eye movements are a part of the perception and so are expected. In general, only events which are unexpected are disruptive and become noticed (Mackay, 1967).

Hebb ascribes an important role to eye movements in visual perception - 'in short, a part-image does not excite another directly, but excites the motor system, which in turn excites the next part-image' (Hebb, 1968). Eye movements have an organizing function since they serve to distinguish the components of a percept. Without such an organization, Hebb argues, perception would be reduced to a jumble of images. Each successive input would overlap with the previous ones and none could be disentangled from the composite which would other-wise form (Hebb, 1968).

Established phase sequences account for the recognition of patterns since the activation of a cell assembly will lead to eye movements, the activation of further assemblies and eventually the activation of the entire phase sequence. While a sequence is becoming active, eye movements are controlled by the sequence itself, though when all the assemblies are active there is no need for further scanning and the pattern is seen as a whole. Further scanning at this stage is not possible since all assemblies will be equally active and no one movement will be any more likely than another.

Eye movements during the learning phase are a different matter since there are no assemblies to initiate changes of fixation. In order to achieve scanning at all, Hebb suggests a basic mechanism which consists of the tendency of the eye to be drawn along a contour until an end is reached. In the example of a triangle, the eye would fixate on a corner, follow one of the edges until another corner is reached and then change direction. For a triangle there would be two possible directions at each corner, and whichever draws the eye most would be followed; If they draw the eye equally, random fluctuations in the background neural activity could upset the balance and produce a movement. Initial eye movements will tend to trace around the contour, for only by fixating all points of a pattern at some stage can a perception of a whole be achieved. This style of scanning has been reported for simple outline shapes (Zusne and Michels, 1964), but it is not the rule for pictures which lack the linear contours to exert such a pull.

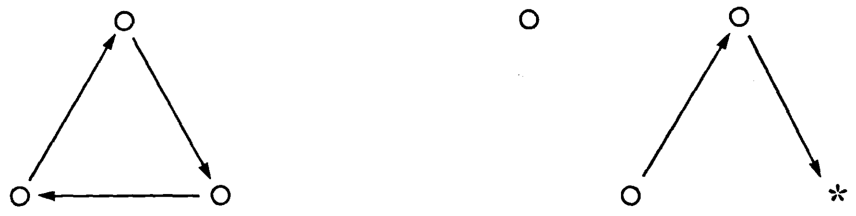
It is interesting that Hebb does not think eye movements provide any perceptual information about patterns - ' ... one may agree with Lashley and the Gestalt psychologists that motor activity in itself cannot possibly explain the organization of perception ...' (Hebb, 1949, p.83). This is surprising since knowledge of the direction of eye movements could supply useful information about the relationships between the features of patterns and so provide a means of coding structure. Of course it is possible that a combination of sensory and motor information may be used, but the impression one gets from Hebb is that sensory information alone is of primary perceptual importance. In an illustration of a phase sequence (Hebb, 1949, p.98) it is only the sensory elements which are shown and distinguished. The eye movement assemblies are mentioned, but play no real part in the representation of the pattern. Hebb uses a metaphor to describe the role of eye movements - 'If line and angle are the bricks from which form perceptions are built, the primitive unity of the figure might be regarded as mortar, and the eye movement as the hand of the builder' (Hebb, 1949 p.83).

Hebb did not stress that the order of scanning a pattern was important, and this means that it could be possible to rearrange some of the features and confuse it with what would be a radically different pattern. The activation of constituent cell assemblies would spread the activation to the whole phase sequence, regardless of the order in which they were seen. Figure 1a shows two triangular arrangements of points and figure 1b shows two different orders of scanning which would both activate the same phase sequence.

To be fair, Hebb does suggest that a phase sequence could detect an alteration by introducing the idea of

a). Two configurations with the same elements.

b). Hebb type scanning. The order is changed but the same features are seen after the same eye movements and the two figures will be confused.



c). Noton & Stark type scanning. Attempting to scan with the same order of eye movements quickly distinguishes the figures at *.

Figure 1. Ordered eye movement sequences will distinguish different configurations.

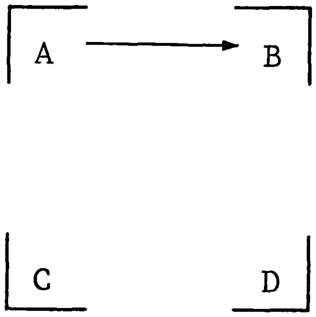
expectancy. Fixation of a feature, followed by an eye movement in a particular direction will lead to the activation of the subsequent cell assembly. Provided this assembly corresponds with the next fixation, the sequence of expected inputs will synchronize with the encountered inputs. A failure to synchronize will be an indication that something new is being seen. Figures 2a and 2b illustrate how such predictions may be made with Hebb's system.

Despite these comments, the neural aspects of Hebb's theory do suggest that activation of only a few assemblies of a phase sequence will spread to the remainder, a mechanism which Hebb put forward as an explanation of 'whole' perception. This would tend to overrule the operation of the expectancy mechanism, and figure 2c shows the pattern of connections between the constituent assemblies of a phase sequence. Because each is connected with all the others, the activation of any one assembly will spread to the others regardless of the order in which they are seen.

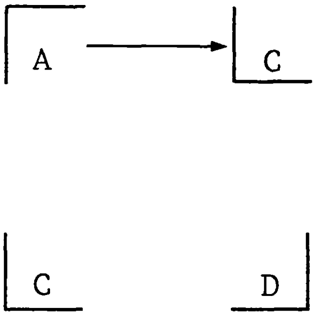
3. The Noton and Stark Theory of Scanpaths.

a) The Habitual Scanpath

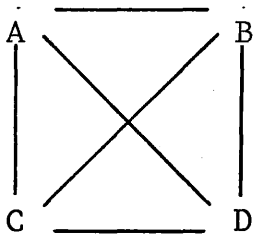
This more recent theory has a similar form to Hebb's but differs in the emphasis placed on eye movements and recognition (Noton and Stark, 1971a, Noton 1969, 1970). Again it is proposed that patterns are remembered as alternating sequences of features and eye movements which link them,



a. Corner B is seen after an eye movement from A. When such a movement is repeated from A, corner B will be expected.



b. C. has been substituted for B. Because B was expected, the two patterns should be discriminated.



c. The connections between assemblies for both patterns. Whenever C is seen, activity will spread to other assemblies. This happens even if C is not predicted, and the patterns will be confused.

Figure 2. Predictions with Hebb's phase sequences and the confusion of patterns.

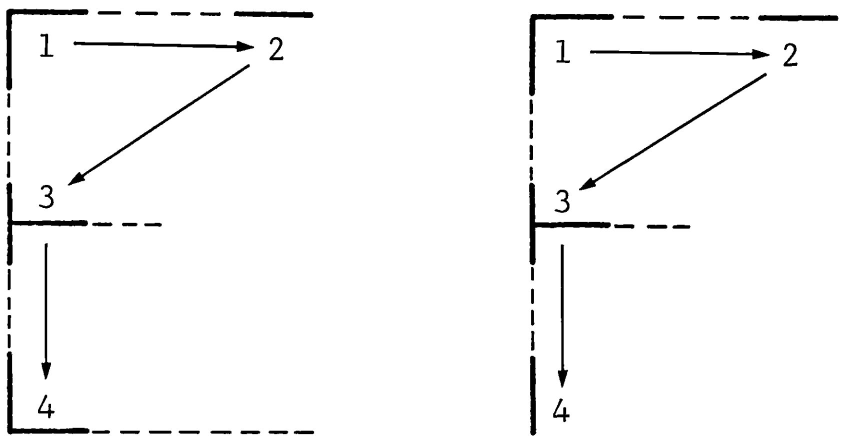
but the restriction is introduced that the order of scanning established during the learning phase will be followed during recognition. Hebb, while not dismissing such an idea, did not emphasise or attach any importance to the order of scanning. Indeed it may be more beneficial if a variety of eye movements are possible at any stage for this will have the effect of achieving a sounder integration of the phase sequence.

In the Noton and Stark theory recognition is achieved by executing an ordered scan of the pattern, directed by the stored sequence of eye movements, and matching the features isolated by each fixation with those in memory. The effect will be to produce scanning habits, and the term 'scanpath' is introduced to describe the preferred sequence of fixations. The scanpath is a habitual sequence of eye movements which appears during pattern recognition because eye movement information is stored serially in memory.

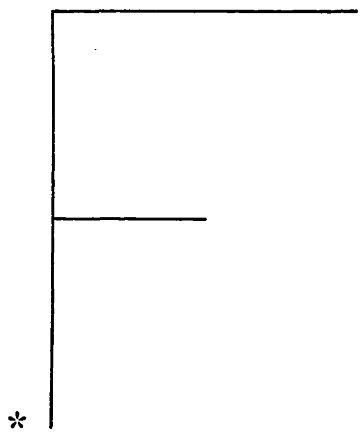
This emphasis on the order of scanning means that eye movements recorded in memory provide spatial information about patterns. This means that re-arrangement of features will not produce the confusions from which Hebb's system suffered, and figure 1c shows how attempting to scan the second triangular figure with the same order of eye movements quickly detects the difference.

Prediction of what the next input might be has a dual function. Firstly, in co-operation with an ordered series of eye movements, it is a means by which a schema may be compared with a pattern. The first fixation on a pattern will identify a feature which may belong to several different fixation sequences stored in memory. An attempt is made to match each of these serially by choosing one sequence and executing the eye movement stored after the feature. This permits a prediction to be made of the next feature which is seen, and a comparison can be made between the expected and obtained features. If the two match, the following eye movement is executed and the next prediction made. When the complete sequence stored in memory can be followed, and all predictions match, the pattern has been identified.

If at any stage in this process there is a mismatch between the expected and obtained features, this indicates that the wrong sequence was being used, and another must be followed. This procedure is illustrated in figure 3, where 2 stored sequences of fixations are shown. Of these, the first will produce a mismatch on fixation 4 when the pattern (a letter F) is scanned, but the second will produce a series of matches. The second function of prediction is to speed up the process of recognition. Noton (1969) describes this aspect in terms of a design for a computer implementation of his theory, but the discussion applies to information processing theories in general. He argues that a pattern



Two stored sequences of features and eye movements. The one at the left records a letter E, the one at the right records a letter F. The two differ in the fourth feature.



When this letter F is scanned, the sequence for letter E will mismatch at *. Scanning with the sequence for letter F will produce a complete series of matches.

Figure 3. Recognition of patterns using stored sequences of features and eye movements.

recognition system which attempts to identify all the features of a pattern in parallel is using an inefficient method. Many of the features may be redundant, and the common technique of storing features in a serial memory means that an exhaustive search through the whole list may be needed. A prediction confines attention to one feature and only one comparison need be made. An incorrect prediction will still require an exhaustive search, but a reasonable proportion of matches will reduce the total time spent on memory search.

b) The Experimental Evidence for Scanpaths.

The scanpath hypothesis receives support from several sources. Yarbus (1967) reported the occurrence of cycles during the exploration of pictures. A 3 minute recording was divided into 25 second blocks and it was evident that the same regions were repeatedly examined in the same order, each cycle lasting about 25 seconds. Zusne and Michels (1964) exposed a large number of random shapes for 8 seconds each, and their illustrations of 7 eye movement records show sequences of fixations which repeatedly occur in the same order, though differing according to the pattern. Jeannerod et al. (1968) showed subjects two pictures for 8 seconds each and then allowed them 18 seconds for recognition. They reported the appearance of cycles during the recognition phase, and noted that these would be repeated several times, the same regions being examined in the same order.

Gould, on several occasions, noticed his subjects would adopt individual styles of scanning small matrices of figures (Gould, 1967, Gould and Dill, 1969, Gould and Peeples, 1970). Although this is probably a technique for ensuring that the matrix is adequately covered, it is interesting that subjects habitually used one sequence of fixations. The use of scanpaths during pattern recognition is suggested by some extraordinary experiments on sensory substitution (Bach-y-Rita, 1972). Blind subjects were equipped with a hand-held camera connected by a processing unit to an array of skin vibrators worn on the stomach or back. The scene before the subject was transformed into a pattern of vibrations, and each individual was free to scan it by moving the camera. Records of the camera movements showed that the same objects tended to be scanned in the same way each time, though when they were very near to the camera these ordered sequences broke down as much of the scene was outside camera-range.

Furst (1971) showed something resembling scanpaths in an experiment involving the repeated presentation of pictures over a series of trials. As the subjects became familiar with the pictures, the number of fixations decreased rapidly. Dividing the record into squares showed that the number of different regions examined also fell with repeated presentations. In addition, for each square, a count was made of the number of times each other square was fixated next. Analysis showed that these first order sequential dependencies became more predictable with each further presentation of a picture. Although only first order sequential dependencies were calculated, this does suggest that familiarity with a picture results in an orderly series of fixations.

Noton and Stark (1971 b) carried out an experiment designed to confirm their hypothesis. Subjects were shown 5 pictures for a period of 20 seconds each. Eye movements were recorded by reflecting light from the subject's sclera onto a photocell. As the eye rotates, the amount of light reflected varies as the iris intersects the beam. With two lights and photocells, both horizontal and vertical rotations can be recorded. An initial calibration is necessary to transform the records into patterns of fixations, though the accuracy of this method can be questioned for the vertical rotations since the lack of visible sclera above and below the iris reduces the sensitivity of the reflected light to record movements.

Following the familiarization trial in which the subjects were just asked 'to look at pictures', the original 5 pictures were mixed randomly with 5 new ones. This group of 10 was shown 3 times, 5 seconds being allowed for each picture, again with the instructions 'to look'. The sequences of recorded fixations were examined for scanpaths by looking for repeated cycles. This qualitative analysis was more concerned with the path followed by the eye rather than with the actual fixations made, since clusterings were treated as one fixation if the cluster was found at the same point in the path.

The data from the several records of each subject allowed the scanpath to be presented in an idealized form based on the composite. Scanpaths were found to occupy 25% of the total viewing time during familiarization, and were repeated for 65% of the time during recognition. Although more time was spent recognizing with scanpaths, it is not clear whether this is due to the rather short period of time allowed. Had the recognition trials been allowed to continue, the subjects might have repeated the scanpath or gone on to explore other details. The average number of fixations per scanpath was less for recognition than learning, and Noton and Stark report that subjects tended to explore the pictures more widely on first viewing.

Some pictures failed to produce evidence of repeated scanpaths, and it is not clear why this should happen. It may be that more than one scanpath can be formed so that each recognition trial contained a different one. The pictures varied in content, and it may be that a familiar object like a telephone encourages subjects to use a variety of existing scanpaths. Some pictures were of nonsense shapes, and such novel material may be more suitable for demonstrating the same scanpaths in learning and recognising. Another reason for the lack of repeated scanpaths may be that some are so long there is no time for it to be repeated before the end of a trial. Yarbus reported cycles of 25 seconds which Noton and Stark's scoring could not have detected.

It would seem premature for Noton and Stark to attempt a revision of their theory on the basis of these somewhat discrepant results without further exploring these points. They suggest that at times short cuts may occur in the scanning so the single ordering they initially proposed is merely a preferred method of scanning, and other eye movements may intervene. This relaxation of the rules brings their theory very close to Hebb's since these alternative eye movements are also stored in memory.

A further modification is included to account for the recognition of objects small enough to preclude scanning. They propose that scanning still occurs, but that it involves internal shifts of attention rather than external eye movements. While the emphasis on the role of eye movements does not rule out perception within the confines of a single fixation, the adaptation of an eye movement theory of this nature simply will not work. The recording of eye movement information means that the position of the target for fixation is exactly specified within a normal sized stimulus display, but the reduction of the display would mean that this information is completely inadequate. A different mechanism is needed to make eye movement information compatible regardless of the size of the stimulus.

Further experimental work is clearly necessary to test the claims of this theory. One possibility would be to record scanpaths and then change parts of the patterns which lie on and off the scanpath. It would be predicted that only changes to those parts of the pattern falling on the scanpath should be detected, and alterations to non-scanpath areas, even if fixated, will not be noticed. Another detail which needs examining is the extent to which a scanpath must be followed before recognition is achieved. Both Noton and Stark's and Furst's data suggest that repeated presentation of a pattern results in shorter scanpaths, and it has been noticed elsewhere that learning often takes longer than recognizing (Gould and Dill, 1969, Mackworth and Bruner, 1970).

c) Problems with the Theory.

There are several difficulties with the Noton and Stark theory which makes it inadequate as an explanation of the control of eye movements during recognition.

1. The theory proposes that each pattern representation is stored as a separate list of features and eye movements. This is an odd restriction when it is considered that one purpose of organized scanning is to speed up recognition by virtue of the predictions which are made about expected features. This advantage may well be lost if a feature is

detected which belongs to several different sequences. In this situation, one sequence must be picked arbitrarily and the pattern scanned to see if it matches. If this should fail, another sequence must be used, but the information which was gained in the first few fixations will be lost, and cannot be used to select another sequence for matching.

If the pattern is a new one, only an extensive search through the whole of memory will reveal this, and the pattern will need to be scanned many times in the process. While the prediction of a feature may speed up feature recognition, repeated attempts to match different sequences may be a lengthy process.

2. The theory implies that scanning should continue unchecked, but clearly some point must be reached when the observer looks away. Noton and Stark(1971a) suggest that the sequences in memory may take the form of closed loops, a proposal which would produce endless cycles of fixations. One solution would be to note where in the sequence fixating begins and terminate looking when this point is reached again, or when there is no more scanpath to follow. This would not account for the decrease in looking with repeated presentations, and such a formulation would have to be modified to permit further looking if one sequence was found to be incorrect and another had to be tried. The strongest argument against this proposal is that it does not explain how the length of

a sequence of fixations is determined when none is stored in memory and a new one has to be learned.

3. The learning of fixation sequences does not receive sufficient attention in the theory. In a description of a proposed computer model which would provide a machine with pattern recognition capabilities (Noton, 1969), it is suggested that 'feature displacement rings (stored sequences of features and eye movements) may either be built into the system initially or be constructed automatically by the system ... from given standard examples of patterns'. The usefulness of these stored sequences depends considerably on the means by which they are created, but it is not explained how they may be 'constructed automatically'.

4. The Didday and Arbib Model

Didday and Arbib (1973) present a theory of pattern recognition which is similar to the Noton and Stark theory in its basic tenets, but they question the means by which scanpaths re-appear. They argue that the strictly serial approach which confines one feature to a fixation is incorrect, and perception is far more a parallel process. They propose that a representation of a pattern will consist of a collection of features organised according to their spatial relationships as a map or 'slide'. When a pattern is seen, visual information is received from two sources. The fovea provides detailed information in the form of specific features while the peripheral retina indicates the general spatial layout of a pattern.

Although the nature of the features in the periphery is unknown, this parallel input may be compared with the slides in memory. All those which contain the specific foveal feature and the general arrangement of peripheral features will be selected as possible matches. At this stage scanning is introduced so that each peripheral feature can be brought to the fovea and identified. This process will reject all slides which share the same spatial layout as the pattern but not the same features.

Didday and Arbib are able to account for the re-appearance of scanpaths by assigning each peripheral feature an interest value. These values are projected onto the eye movement computing system which corresponds with the mammalian superior colliculus. The feature which has the highest value is selected for fixation, and where a choice exists, competition is allowed until one dominates the system (eg. background levels of excitation may fluctuate rather like Hebb's system). Each time a feature is fixated and correctly predicted it is deleted from the collicular system and cannot be re-fixated. With this mechanism, fixation begins with the highest value and continues successively through the lower ones. Scanpaths naturally re-appear because the interest values repeatedly produce the same sequences of fixations.

This theory is similar to the serial habituation hypothesis (Jeffrey, 1968) which proposes that stimuli consist of a number of cues with different attention levels. The one with the highest level controls attention, but over time habituation reduces its hold. At this stage the next most salient cue captures attention, and so on through the remainder. The repeated appearence of this series of attentional changes will establish a schema for the object based on its component cues, a procedure which is very similar to the Hebb and Noton and Stark theories, but explains how schemata might form.

The Didday and Arbib theory also resembles a computer model which remembers and perceives chess positions (Simon and Gilmartin, 1973). Pieces are given a saliency value (like the interest value of a feature) depending on their location on the board. Chess positions are remembered by recording the arrangements of a small number of pieces relative to a high salience piece in a map or snapshot (Zobrist and Carlson, 1973). Each of these clusters of pieces is recognised by starting with the salient piece and checking for the remaining pieces and their positions in a serial fashion, a process the authors note corresponds to the Noton and Stark scanpath (Simon and Gilmartin, 1973, Simon, 1972). By coding the whole chess board with a number of these maps, the program is able to remember from 39% to 73% of the total number of chess pieces. In addition, the program scans the board in a fashion resembling a chess expert (Simon and Barenfeld, 1969).

Didday and Arbib have also simulated their model with a computer, but introduced several simplifications. Visual pre-processing of patterns is not included, and patterns are presented to the system by providing the position co-ordinates of the features and the interest value that each possesses. The simulation does not recognize patterns because there are no slides stored in memory, but it does show sequences of fixations. While these are not repeated scanpaths because fixation sequences are not retained in a long term memory, the model can produce different sequences of fixations for the same pattern. This is achieved by altering the interest values of the various features, and may be interpreted as reflecting the different preferences of different observers.

Similar objections may be made to this theory as to the Noton and Stark version. It is not at all clear how the slides which contain the pattern representations are formed, and how scanning would occur in the absence of any slides. The interest values of the features are the essential components which produce scanpaths, but no attempt is made to establish why some features should have greater values than others. In the simulation they are determined by the operator before the program is run on the computer, and not by the program itself.

The problem of the control of the length of a series of fixations also exists with this model. It is clear that the whole series of features will be examined, and when complete there will be nothing further to look at because of the mechanism which deletes fixated features from the colliculus. This does not explain how scanpaths would become shorter the more frequently a pattern is seen nor how long the series will be for the first presentation of a pattern.

5. The recording of Eye Movements in Memory.

One difficulty with both the Hebb and Noton and Stark theories is the importance they place on the recording of actual eye movements. It is this aspect which Haber and Hershenson (1973) feel compelled to criticise '... it is difficult to see how perceivers store information on the sequence of their fixations ... it would seem a very complex way of coding information ...' This aspect can be tested by seeing what happens when vision is restricted to the fovea with the exclusion of the periphery. If eye movements are recorded it would be expected that this radical change of input would have little effect on scanning and recognition. Hebb did allow for peripheral information to be recorded at each fixation and its absence might affect recognition, but the features detected foveally were more important in his theory and were the main contributions to cell assemblies.

This peculiar condition has been observed in several patients and produced experimentally. Tyler (1968) reported a patient suffering from Balint's syndrome. This condition reduces the patient's visual capacity to seeing only one unit at a time, where the unit may be a whole figure or simply a part or feature. Tyler's patient, after a lifetime of normal vision, suddenly developed visual difficulty which manifested itself as a reduction of active fields to a mere 2 degrees on either side of the point of fixation. This could be improved to about 20 degrees if a test session was beginning, but fatigue rapidly reduced this improvement.

This patient was not blind nor aphasic and could see perfectly well if shown pictures smaller than 2 degrees, but could only handle larger pictures with extreme difficulty. Tyler tested her on several pictures and recorded her eye movements. She continually guessed at what she was shown, trying to identify the tiny fragments but never synthesising a whole. The only pictures with which she had any success were of a small box or square where she fixated each corner in turn, but Tyler does not say how large these pictures were or whether during this test she still had some peripheral vision.

An examination of scanning patterns showed that exploration was completely different from normal subjects. There was a tendency to remain fixated on one region, and when shifts of attention were made, they were unrelated to the pictures, often wandering outside the frame which made it difficult to re-locate the picture. Showing the pictures again elicited no improvement in scanning and again she only saw parts. Identification of objects as familiar as the American flag was impossible, though when told the identity she was quickly able to comprehend what she had been seeing.

Tyler interpreted this patient's defective exploration as being entirely due to the reduction of her visual field. He rejected the notion that she was suffering from an agnosia since her behaviour at other times showed no impairment of congnitive ability, even though aphasic patients may also show inadequate scanning (Tyler, 1969). Of course, we cannot rule out the possibility of lesions in the oculomotor system itself, but Tyler prefers the simpler explanation that the perceptual difficulty was due to an inability to fixate the informative areas of the pictures.

The necessary control experiment was conducted by Andreeva et al. (1972). The visual fields of normal subjects were artifically restricted to 3 degrees around the point of fixation by means of a suction cap placed on the cornea. This had the same effect as the restriction with Tyler's patient, and the subjects were unable to recognise even outline drawings of simple shapes. In addition, recordings of their eye movements showed the same dis-organization, and the authors concluded that it is vision which determines eye movements, not the reverse.

These two findings suggest that on this crucial point concerning the recording of eye movement information both the Hebb and Noton and Stark theories are incorrect. Before we reject them completely we should consider whether some other interpretation is possible which will account for the appearance of scanpaths. One clue comes from the suggestion that eye movements serve to relate the parts of a pattern or picture (Mackworth and Bruner, 1970, Zinchenko, 1970, Piaget, 1969).

Consider the situation where a pattern is being scanned for the first time and a schema is being constructed in memory. A number of features are identified at the point of fixation and around this point the remainder of the pattern is seen only indistinctly. The peripheral retina indicates the extremities of the pattern, but only the presence of contour is registered, not the detailed information which a fixation alone can supply. At this stage an eye movement must be made and one region singled out as a target. We need not consider yet how this target is chosen; a scheme such as Hebb (1949) outlined may be sufficient. Once a target has been selected, a saccadic eye movement will be executed to bring it to the central zone of vision. Again, we need not consider how this saccade is effected save to note that it is achieved by a reflex mechanism (Robinson, 1968).

It is at this point that the two eye movement theories specify that information about the eye movement is recorded, but it can be seen that another possibility exists. Prior to the saccade, a target was selected and all that need be stored is information about the location of this target. This form of representation still allows a sequence of features and eye movements to be recorded and reproduced during recognition, but the control of eye movements is indirect. The eye can be guided by picking out the appropriate peripheral target at each stage in the scanpath and so biasing the action of the reflex.

The Didday and Arbib model makes a similar proposal, and this strategy also allows more information to be registered since the peripheral target will be stored along with the features detected foveally. The failure to recognise and scan properly when vision is reduced can be explained as a lack of targets to fixate, and the scanpaths could not be followed because of this essential element.

This interpretation receives some support from studies with patients exhibiting simultaneous agnosia (Luria et al., 1964, Luria, 1973). Luria et al. studied such a patient who could only see one object at a time, regardless of its size. This deficit was not due to a narrowing of the visual fields since the object could have any size. The patient was unable to see two objects at the same time, and his scanning was very abnormal because of this defect. He was unable to fixate one region with central vision, and still perceive a target in the periphery.

Luria et al. recalled a discussion of similar defects by Pavlov, whose explanation for this condition was that one stimulus had an overwhelming inhibitory effect on another, hence only one could be perceived. It was reasoned that an injection of a stimulant would overcome the inhibition and restore normal vision. A solution of caffeine was administered, and shortly after, visual performance improved considerably so that the disparate elements in the pictures could be seen in relation. As the effects of the drug wore off, perception returned to its original level and single elements were again seen in isolation.

The authors concluded 'The reflex shifting of the eye ... is possible only if there is a system of simultaneously excited points. Some of these points (peripherally located) constitute the source of impulses inducing reflex shifting of the eye, and others (central in location) bear the function of reception and transmission of visual information.' (Luria et al., 1964, p. 38).

6. Peripheral vision and the location of a target

In this thesis it is assumed that visual input is divided into two types, one which is central and concerned with specifying features and the other which is peripheral and concerned with locating targets to fixate. This distinction is maintained in the brain and two kinds of visual system have been isolated which carry out these functions.

a). Subcortical visual systems and spatial information

The brain systems which are concerned with spatial information and the location of targets have been demonstrated in several studies. Trevarthen (1968) conducted split-brain experiments with monkeys in which the optic chiasma and forebrain connections were severed. This means that each half of the brain only receives input from half of the visual field on the opposite side. A pattern shown to the left half-brain will not be recognised by the right, though with certain restrictions. Detailed pattern discriminations were not transferred from one half to the other (for example a cross and a circle or horizontal and vertical bars), but pattern attributes such as colour, brightness and relative size were transferred. The only path available was via the mid-brain visual systems which were still intact. Trevarthen emphasises the role of this system in ambient vision which is concerned with supplying a spatial framework within which focal vision may operate.

In further studies with patients having separated hemispheres, Trevarthen (1970) was able to describe more fully what such ambient vision involved. In these patients, visual input to the left visual field is registered in the right hemisphere, and provided the speech centre is located in the left hemisphere, they are unable to report details of the input processed by the right hand cortex. Anything reported in this situation must have been transferred by the subcortical visual systems, and the finding was that spatial information dominates this system. Motion and its direction are readily detected, and even simple features can be identified, but familiar objects are never recognised unless some distinctive feature gives them away.

Humphrey (1970, 1972) reported some experiments carried out with a monkey in which the visual cortex had been surgically removed. After recovering from the operation it was found that the animal had considerable visual ability. She was able to walk around obstacles in a test room while searching for small currants on the floor, and her spatial ability was sufficient to locate these tiny objects. She could learn to discriminate patterns, but only on the basis of size or brightness and never for form. These tests were conducted by recording which stimuli would elicit a reaching response, rather than teaching different responses to different stimuli since the monkey could never learn such a task. Again the conclusion is that while the cortex is concerned more with detailed processing and recognition, the mid-brain handles the detection of the presence of objects and their location in space.

These observations on two distinct visual systems lend support to the idea that visual representations have two components. One the one hand there is the 'what' aspect, concerned with analysing and identifying, and on the other is the 'where' aspect, concerned with locating the next target to fixate and control of eye movement (Schneider, 1967).

b). The superior colliculus and Eye Movement control

One mid-brain structure of importance for eye movement control is the superior colliculus. Its involvement in spatial behaviour was shown by Schneider (1967). Two sets of hamsters were prepared by removing the visual cortex in one and the superior colliculus in the other. Cortex-intact animals were successful on a variety of discrimination learning tasks, but colliculus intact animals were only capable of learning when the discrimination involved gross differences such as brightness or orientation of parallel lines. When a test was conducted for localization and rearing towards a moving stimulus, only the colliculus intact animals showed any success. The others noticed the stimulus but failed to orient towards it and 'froze'.

These differences between the groups also showed up as two strategies in a discrimination task. Normal animals were able to move directly towards the correct door in a two-choice maze, but those without a colliculus would often go up to the wrong door and only then correct their mistake when they could see the stimulus. They did not have to push against the door to realize their error, and it would seem that they were unable to make the correct move initially because they lacked a spatial visual system.

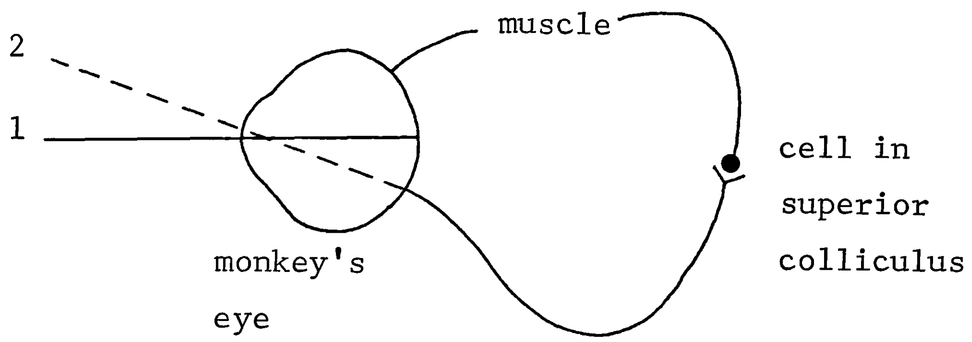
The superior colliculus also has a direct action in producing eye movements. Apter (1945) mapped out the superior colliculus of cats by inserting an electrode and recording from various cells which were activated by a small point of light flashed onto the retina. She discovered there was a point to point mapping from the retina onto the colliculus so that each collicular cell corresponds to a particular retinal region. In addition she found that these collicular cells were involved in eye movements. Strychnine was applied to individual cells in the colliculus and the retina illuminated with a diffuse light. The hypersensitivity of the strychninized cells caused them to fire, and an eye movement occurred. A map of the points in the visual field which were fixated after this procedure coincided with that previously obtained by stimulation, and it would seem that the point stimulation of any part of the retina is converted by the colliculus into an appropriate eye movement to fixate the stimulus, (Apter, 1946).

This observation has been studied in detail with Rhesus monkeys (Schiller and Stryker, 1972) by stimulating and recording from the superior colliculus using the same electrode. It appears that each cell initiates an eye movement of a particular size and direction, regardless of the position of the eye in the orbit. The movements are all-or-none since increases in the stimulating current did not alter the size of the saccade, and while long stimulations would initiate several saccades, each was of the same size. Figure 4 illustrates the operation of the superior colliculus in producing eye movements.

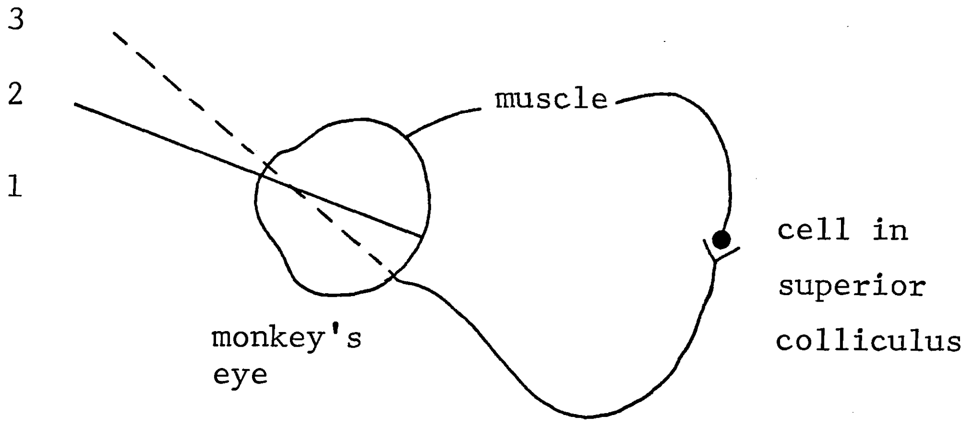
c). Biasing and the Control of a Distributed Motor System

This physiological evidence indicates that the mid-brain visual system processes spatial information, and the superior colliculus is capable of supplying the location of a target to fixate and initiating an appropriate eye movement. Instead of recording details about this saccade in the schema, all that need be registered is the means by which the colliculus may be controlled to produce the same eye movement. Without considering at this stage how the superior colliculus might arrive at a decision about which region to fixate, it should be pointed out that the problem is one of choice.

A pattern will stimulate a wide area of retina and consequently a large number of different cells in the superior colliculus, each one capable of producing a different eye movement. Pitts and McCulloch (1947) made the suggestion that



a. The eye is fixating point 1, but a cell in the superior colliculus responds to stimulation in its receptive field from point 2.



b. The superior colliculus produces a reflex movement of the eye so that point 2 is fixated foveally. The receptive field of the collicular cell now covers point 3.

Figure 4. The operation of the superior colliculus to produce eye movements.
(adapted from Blakemore, 1973).

rather than let any one cell dominate amongst all those activated, an eye movement is made which is the resultant of all those which individually would be possible. Arbib (197~~3~~2) has elaborated this concept of 'distributed motor control' and concludes that for a network organized like the superior colliculus '... there is no 'executive Neuron' that decrees which way the overall system behaves; rather the dynamics of the effectors .. extracts the output trajectory from a population of neurones'.

This kind of system poses problems for the type of control which could be exerted on it. Recording the location of the cell which alone could produce the resultant eye movement would not be enough. Simply activating that cell to reproduce the saccade might not work if the pattern of activity in the remainder of the superior colliculus is altered (which might happen if the pattern is shown in new surroundings). At this point the discussion must become speculative since little is known in detail about the systems which interact with the superior colliculus (Robinson, 1971).

One useful suggestion concerning the control of reflexes is Pribram's (1971) concept of biasing. The range of a simple TOTE system can be expanded if the 'OPERATE' section is susceptible to variation. Pribram gives an example of such biasing in a discussion of the muscle spindle servo system which governs the contraction of muscles (Merton et al., 1956).

The length of a muscle can be kept constant by means of a negative feedback loop controlled by length detectors (spindles) attached to the muscle. This may be very useful if the load on a muscle is changing and tending to alter its length, but if the setting on the spindle permits only one length its usefulness is questionable. Variable lengths can be permitted if the setting of the spindle can be altered, and mechanisms which allow this have been found. The outcome is that while the basic servo system operates as a reflex, its operation can be biased to achieve both large and small contractions.

This idea of biasing requires that whatever control is operating on the reflex must be compatible and permit the reflex to function normally. The superior colliculus requires an input to produce an eye movement, but this input may be altered (for example by inhibition), and so can be biased. It is suggested that eye movements may be recorded as a systematic biasing of the natural operation of the superior colliculus, but an input will still be required if it is to function normally. For this reason, the reduction of visual input by the exclusion of peripheral stimulation will produce inadequate scanning. Further discussion of the recording of fixation targets and biasing of the oculomotor reflexes will be continued in the description of the computer simulation.

7. Features and Targets in memory

It is proposed that each fixation on a pattern will establish in memory a record of the features detected on the fovea, and an associated target region in the periphery which will be fixated. This combination will be referred to as an 'analyzer' or perceptual unit with which the input may be classified during a fixation. It is important to note that each analyzer has components derived from central and peripheral vision, but the peripheral component only records information about the location of the target region, and not what features might exist at that position.

This description of analyzers resembles Sutherland's (1959, 1964, 1968) use of the term. Sutherland investigated stimulus processing mechanisms during pattern discrimination learning, and suggested there was a bank of analyzers, each capable of picking out different aspects of the stimulus display. These analysers were thought to correspond with the clusters of features detected by cortical processing (Hubel and Wiesel 1962). The analyzers discussed here are similar, but also include a peripheral component. In addition, while Sutherland considered analyzers to be largely innate, this restriction is not made here, and they may be acquired while patterns are scanned.

Deutsch (1960) also used the term 'analyzer' to describe stimulus processing mechanisms, but these were linked directly to some motor response system. This linkage is similar to the peripheral component, since specifying a peripheral target region is a means by which the appropriate response (eye movement) may be produced.

Analyzers contain two sorts of information, central vision supplying details about the pattern area fixated, and peripheral vision indicating where to look next. This means that an analyzer is a sensory-motor unit, recording sensory input and (indirectly) an associated eye movement. A similar position is held by Hochberg (1968, 1970, 1972), with his concept of a 'schematic map'. Hochberg argues that there must be some central representation which consists of the information picked up with each fixation, organized into a spatial framework or 'map'. This structure has the extra function of directing eye movements during the scanning of a figure. An analyzer, as described above, may be regarded as a means by which this spatial organization and eye movement control might be achieved.

In order to record a series of fixations which may be repeated during pattern recognition, it is only necessary to store the first order sequential dependencies between analyzers. Each analyzer is assigned a list of analyzers which have been seen on the following fixation. This list may then be used to generate predictions about what might be seen next when the eye movement implicit in each analyzer is executed. In this manner the various parts of a pattern are placed in spatial relation to each other, the peripheral visual component specifying this relation. The need for this to distinguish different configurations of the same features was noted earlier, and several artificial pattern recognition systems have successfully used this approach (Barrow and Popplestone, 1971, Guzman, 1968, 1971).

Although complete sequences of fixations are not stored separately as in the Noton and Stark system, scanpaths will still be repeated when patterns are recognized. This will happen because each analyzer contains a peripheral visual component which initiates an eye movement. When an analyzer is identified during pattern scanning, this peripheral component will result in an eye movement being made to fixate the target area. The new fixation allows another analyzer to be identified, and the process will be repeated. Identifying the same analyzers on patterns which have been seen before automatically produces a repetion of the original scanpath.

It should be pointed out that such a scheme will only permit pattern recognition but not pattern identification. These two concepts are often regarded as equivalent, for example when perception is treated as a process of categorization (Bruner et al. 1956). Recognition is best regarded as the knowledge that something is familiar, while identification is knowledge of what something is. We are often able to recognize a face, but identification means we are also able to supply a name. Pattern identification will not occur by recording only first order sequential dependencies because different sequences of fixations are not stored separately, and it would not be possible for the memory to specify which sequence was being followed during scanning. Pattern recognition alone is possible, provided that an analyzer can be identified at each fixation which matches the prediction. Recognition will also be accompanied by the re-appearance of scanpaths, as each analyzer which is identified necessarily implies an eye movement.

CHAPTER 3.

THE CONTROL OF VISUAL ATTENTION AND THE DISCREPANCY PRINCIPLE.

1. Introduction

The theory developed so far describes how patterns are learned while the eye scans around them, and how schemata are formed which control subsequent scanning to achieve recognition. In this discussion, nothing has been said about the processes which operate to control the length of a sequence of fixations. For any piece of behaviour it is as important to explain why it stops as it is to explain why it begins. All of the eye movement theories which have been considered ignore this aspect and are concerned with mechanisms to produce a series of fixations, which left to their own devices would continue unchecked.

It is proposed that the length of a sequence of fixations is determined by the degree of novelty of the pattern which is scanned. A pattern may vary considerably in this dimension, ranging from well-known and familiar to completely new and strange. Only patterns which are mid-way between these extremes will encourage a long series of fixations, while those which are too familiar or too new will make the eye look away.

This arrangement has the advantage that it is applicable both to very familiar patterns and also to those which are novel and for which there is no schema. The assessment of novelty depends on the relationship between the schemata in memory and the patterns which are seen. The terms 'novel' and 'new' should not be regarded as describing how recently a pattern has been seen, but refer to how alike or unlike a schema a pattern may be. It is the amount of discrepancy between the two which is important, and the relation between discrepancy and attention is known as the discrepancy principle. This principle will be described in the following section, and the evidence which supports it and predictions which may be derived from it will comprise the remaining sections.

2. The discrepancy principle.

This hypothesis is concerned with the determinants of attention and proposes that it is the discrepancy which exists between a schema and a stimulus which is critical. There is a curvilinear relationship between attention and discrepancy which can best be described as an inverted 'U' curve. At the extremes of the discrepancy range attention is least, but between the two there is an optimal level for which attention is maximal.

This type of relationship has been proposed in many different contexts, particularly where the motivation of behaviour is considered. Hebb (1949) suggested that only moderate violations of expectancy would produce approach behaviour, extreme violations resulting in fear and emotional disturbance. Dember and Earl (1957) put forward a theory that an inverted 'U' relation exists between degree of stimulus complexity and subject preferences. Berlyne (1960) described a similar theory, including stimulus incongruity and novelty as well as complexity. His theory suggested that these stimulus variables contributed towards the subject's level of arousal. This has an optimal level which the subject attempts to maintain, so stimuli which promote low or high arousal are avoided. Hebb (1955) made a similar point in a discussion of the relationship between arousal and learning.

An inverted 'U' relation has been put forward as the basis of the achievement motive (McClelland et al. 1953, Atkinson, 1957), but here it is the expected probability of success at a task which is important. The strength of motivation is low for tasks which are seen as too easy or too difficult, but maximum for intermediate values. While this example is a little remote from the present discussion, there are several instances of the application of an inverted 'U' relationship to cognitive development, notably Piaget (1953), Hunt (1965) and Kagan (1970, 1971). All these writers stress that it is a stimulus which is moderately discrepant from a schema which receives most attention.

It is important to specify the nature of discrepancy for this theory, and clearly this hinges on the structure of a schema. Generally this is conceived as a record of the spatial and temporal arrangement of the stimulus components (Bartlett, 1932, Kagan, 1971). This conception is similar to the description given by Piaget (1953) in his study of infant development, but he also emphasised a motor component which gave the schema an important role in organizing the infant's actions. Kagan (1971) does not stress this component, and considers a schema as consisting only of stimulus elements in a particular arrangement with no associated record of actions. Kagan adopts this point of view because he feels that much of early visual behaviour does not involve action of the kind that Piaget described. Despite this, some action is necessary as demonstrated by eye movements, and the indirect inclusion of eye movement information in schemata as fixation targets is a means by which the difference between the Piaget and Kagan interpretations may be resolved.

When there is a correspondence between a schema and a stimulus a state of 'Match' exists (Hunt, 1965) and the stimulus will not command much attention. A discrepancy arises when some aspects of the schema and stimulus 'Mis-match' which will make the stimulus more interesting and consequently it will receive more attention. As the number of mis-matching elements rises the stimulus will receive more and more attention until the optimal number of mis-matches is reached. From this point onwards any further increases in the number of mis-matches will produce a reduction in attention. The most extreme case here is a stimulus which is completely new and therefore mis-matches with every schema. As a consequence this stimulus will receive minimal attention which is the same as the reaction to a familiar one. This equivalence in terms of attention between familiar and novel stimuli should always be remembered when interpreting patterns of looking where measures of attention could confuse the two stimulus types.

The discrepancy principle is important for the development of perception because it exerts a continual 'thrust' forwards. It acts like a protective mechanism which ensures that an infant does not spend too much time looking at stimuli he knows and can learn nothing new about. At the same time it prevents him looking too long at stimuli which are unknown and for which considerable effort might be needed to produce a schema. Attention is dominated by those stimuli which are only partly known, and as a result a more complete schema will form. When this occurs they will release their hold on attention which will then be available for learning something new.

3. Evidence for the discrepancy principle

There have been a number of attempts to test for the predicted effects of the discrepancy principle on looking behaviour with varying degrees of success, and the expected decrease in attention with instances of extreme discrepancy has been particularly difficult to obtain.

McCall and Kagan (1970) used a short term technique for establishing a schema. The standard pattern was shown to infants for 5 training trials of 15 seconds each. Following this, a discrepant pattern was shown for 1 trial, then further exposures of the standard and other discrepant patterns. 3 degrees of discrepant patterns were used in which either 1, 2 or all 3 elements of the standard were altered. The length of the first look was measured and it was found that discrepant patterns were looked at more than the standards which came directly before and after the change. The overall data showed no differences in looking according to degree of discrepancy, but when the results from infants who had failed to show a decrease in attention to the standard were subtracted, it was shown that more discrepant patterns were looked at longer.

This finding was further examined by McCall et al. (1973). In this study a simple stimulus consisting of a double-ended arrow was used, discrepant patterns being produced by altering the orientation of the stimulus. Infants were trained on one of two standards until their looking failed to decrease any further and they were habituated. At this point it was reasoned that the standards had been learned and a schema acquired.

3 discrepant stimuli were then shown and the length of the first look recorded. The infants who had habituated quickly to the standard showed the predicted inverted U relation between amount of looking and discrepancy, but for the slower infants the relation was linear.

Kagan (1971) reported that young infants look more at a normal photo or drawing of a face than at a scrambled version. He argued that this would be predicted by the discrepancy principle if these young infants had only begun to form a schema for a face. At such an early stage the normal face is optimally discrepant while the scrambled version is too extreme. Older infants show the reverse effect, and assuming they had a better face schema, the scrambled faces had now become optimal (McCall and Kagan, 1967).

A further study with older infants (27 months) used a series of stimuli made from dolls. One was a normal doll, another had the head placed between the legs, a third had the body and limbs disarranged and the fourth and most discrepant version simply had a free form of the same general size and colour as the original doll. Recording the length of the first look showed that the two intermediate discrepancy stimuli elicited longer looks, and the predicted inverted U curve was obtained.

Another study which partly supports the discrepancy principle used infants of 6 to 12 months age (Parry, 1973).

The stimuli were simple arrangements of 1 to 4 dots on a circular background, and either the 1 dot or 4 dot stimulus was used as a standard. A short term schema was established by showing these standards for 6 trials of 20 seconds each, learning being demonstrated by the decline in attention over this period. On trial 7 one of the discrepant stimuli was shown, and both groups responded to this with an increase in attention. The significant finding was that the increase depended on the degree of discrepancy, so that a 1 dot stimulus followed by a 2 dot discrepant version produced little increase, while the 4 dot discrepant version produced a much greater effect.

This finding is interesting because appropriate controls are used. When the 1 dot pattern is the standard, the 3 dot one is discrepant and receives considerable attention, yet when the 4 dot pattern is standard, the 3 dot one is far less discrepant and consequently receives less attention. If the amount of looking was controlled by the stimuli alone, these difference would not occur. Instead, by establishing either one schema or another, the stimulus can be made interesting or un-interesting.

The importance of suitable controls was stressed by Super et al. (1972). They point out that the stimuli labelled 'discrepant' may well be interesting in their own right, regardless of the schemata which the experimenter may have tried to establish. In the first stage of their study, infants were shown a standard pattern for 6, 30-second trials and their amount of looking recorded. Each was then shown a stimulus hung over their cot at home for about 20 minutes a day for 3 weeks. These stimuli were all discrepant to some extent, ranging from no discrepancy (same as the standard) through mild discrepancy (simple differences from the standard) to extreme discrepancy (no relation to the standard). One group was shown no stimulus at all at home.

The infants were re-tested with the original standard stimulus, and the change in their looking at this stimulus over the 3 week period noted. Infants who had seen no intervening stimulus showed no change so no significant maturational influences could disrupt the results. Infants who had seen the standard or minimal discrepancy stimuli showed decreases in looking, while those who had seen the intermediate discrepancy stimuli also showed a decrease, but far less than for the others. Infants who had seen the extreme discrepancy stimulus showed as big a decrease as those who had seen the standard, and this pattern of results for the change in looking takes an inverted U form.

Superficially this result would seem to fit the hypothesis, but closer inspection reveals an inconsistency. The initial exposure of the standard stimulus showed that it was quite interesting for these infants. Following the

3 weeks exposure to discrepant stimuli, interest in this standard declined, though the amount depended on the degree of discrepancy. Exposure to the standard or a stimulus very like it meant that there was now a schema which matched the standard and so it became un-interesting. Training with a moderately discrepant stimulus did not produce a matching schema, and this fact, coupled with whatever discrepancies made the standard interesting on its initial test, served to produce the negligible decline in attention. The problem lies with the extreme discrepancy group. These infants will also have developed a schema which did not match the standard and consequently what made this standard interesting before should also make it interesting again. This was not the result which was obtained, and there would seem to be no reason for the decline in this group's attention.

These results suggest at least a partial confirmation of the discrepancy principle since the degree of discrepancy does influence looking. Similar results have also been obtained with adult subjects (Nunnally et al., 1969). In this study it was found that subjects preferred to look longer at more incongruous stimuli such as a picture of a car with square wheels and a sail. The decline in looking which might be expected with increasing incongruity was not found, and further experiments have also failed to produce this result (Durham et al., 1971).

One of the reasons for this failure may be that too narrow a range of stimuli is used (Parry, 1973, McCall et al., 1973). In the experiments with adult subjects the incongruous stimuli were constructed from familiar pattern elements put into unusual combinations. From the discussion in section 2, it could be argued that such stimuli will always be optimally discrepant since they contain a mixture of familiar and unfamiliar elements. Extreme discrepancy with the capacity to inhibit looking requires stimuli to be unfamiliar and unrelated to any schemata, a condition which is not the same as incongruity.

The problem with the infant studies probably arises because all the stimuli used to demonstrate the discrepancy hypothesis are initially interesting to the infants. Consider the Parry (1973) study which established a schema for the 1 dot pattern yet found that the (experimenter defined) extreme discrepancy 4 dot pattern is highly interesting. This result is hardly surprising since the results obtained when this 4 dot pattern was the standard reveal it was interesting anyway. If we assume that the discrepancy principle operates continually and not just during experiments it must be concluded that the schemata the infants brought to the test situation produced this effect.

This suggests that the inverted U relation could be obtained only if initially extremely discrepant and un-interesting stimuli were used. One would be selected as the standard for which a schema would be established, and the effect would be to make only those stimuli which the experimenter defined as moderately discrepant more interesting than they were at first. By using extremely discrepant stimuli more control is gained in the experimental situation, and the infant's previous experience will not be involved. To date no such experiment has been reported, and one of the difficulties may be to find suitable stimuli.

4. The discrepancy principle and its predictions concerning development.

One of the most interesting applications of the discrepancy principle concerns the predictions which may be derived from it about infant perceptual development. The principle specifies that what is optimally discrepant and therefore interesting to an infant is determined by the kinds of schemata which have been established. This suggests that different kinds of experience will affect which stimuli are looked at most, and this should be shown by infants of different ages.

One study which shows such an effect was conducted by Greenberg (1971). The discrepancy principle was not mentioned in his report as the independent variable being examined was stimulus complexity. This was manipulated by using chequerboard patterns with various densities of black and white squares. Complexity is a difficult dimension to define, and a variety of alternatives have been used such as the number and arrangement of stimulus elements (Fantz, 1966), number of flashing lights (Cohen, 1969), amount of contour (Berlyne, 1958), number of corners (McCall and Kagan, 1967) or more typically, as in the Greenberg study, by the number of squares in a chequerboard, (Hershenson, 1967). Considering this disagreement, it would not be too great a violation to suggest that chequerboard patterns be considered as examples of standard and discrepant patterns since some aspects are common (black and white squares) but others vary (number and density). Complexity cannot be considered an independent dimension as it interacts with novelty and discrepancy.

Greenberg presented 3 groups of infants with chequerboards of 64 and 576 squares, each having the same area. All of these infants preferred looking at the 64 square pattern as measured by the total time spent looking. These groups were then given stimuli which were shown for two periods of 20 minutes a day for 2 weeks. One group was given a gray, control stimulus, another was given a 16 square chequer and the third was given a 'pacer' stimulus of 144 squares. At 10 weeks of age they were retested on the original stimuli and it was found that the group which had seen the 'pacer' looked more at the 576 square chequer than either of the other groups who preferred the 64 square version. It would seem that the experience with the pacer altered what the infants considered an optimally discrepant stimulus.

The experiment was continued, but the pacer was changed to a 256 square chequer and the other training stimulus to a 36 square chequer. On a third test at 12 weeks these two groups were looking equally more at the 576 chequer than the group trained with the gray stimulus. This is interesting because it suggests that other visual experiences may have been operating to make the 576 chequer interesting for the group trained with 36 squares. Maturation cannot account for the results since the gray trained group had different preferences.

The interpretation Greenberg offers is that experience with the patterned stimuli made the test stimulus interesting, a conclusion which is in accordance with the discrepancy principle. He further suggested that experience with the patterned stimuli may have induced these infants to explore their surroundings more fully. In terms of the discrepancy principle this means that the more schemata the infant possesses, the more stimuli in his surroundings will become interesting and the more he will look. This is significant as it implies that schemata co-operate in producing optimal discrepancy, and their field of application is wide ranging. The tendency in the literature is to regard discrepancy as arising from one narrowly defined schema and a discrepant stimulus carefully constructed by the experimenter. Yet as was pointed out earlier, it is often the case that on the very first exposure to a standard stimulus the infant finds it interesting. If this is interpreted as an indication that the stimulus is optimally discrepant, the source of this discrepancy must be the schemata which the infant has acquired from previous looking.

If this is the case it can be predicted that as infants become older and have more visual experience, they will become interested in a greater range of stimuli, and there will be a developmental preference for novelty. Fantz (1964) has shown this effect with infants ranging from 6 weeks to 6 months. They were shown pairs of patterns for 10 trials, the positions being exchanged half-way through a trial. During the experiment one pattern was kept constant while the other was changed on each trial. It was found that infants of 2 months or less looked equally at both patterns, but older infants showed a progressive tendency to look more at the variable one at the trials progressed. This result would seem to indicate a developmental preference for novelty.

Greenberg et al. (1970) reached a similar conclusion with 1 month old infants who were shown a pattern hung over their cots for 4 weeks. Tests of amount of looking at this pattern and other novel ones were conducted at 2, 2.5 and 3 months. Although some patterns were clearly more attractive than others, this factor was controlled and on the first test it was found that significantly more infants looked longer at the pattern they had seen than one which was completely new. On later tests this finding was reversed, and new patterns were preferred. The authors noted that although there were age differences for the occurrence of this change, it was always in the order of preference for the pattern which had been seen, followed by the one which was new, and not the reverse.

This finding is even more suggestive of a discrepancy principle explanation. Younger infants have little visual experience since they sleep for long periods, and consequently the pattern hung over their cots must have provided the majority of their visual stimulation. Initially this pattern will bear no relationship with any existing schema, and so will be extremely discrepant. As learning proceeds and a schema is established, this situation will change so that the pattern becomes partly known and partly unknown ie. optimally discrepant. If the first test in the Greenberg et al. study was made at this point, the result would be due to the pattern the infants had seen hung over their cots being optimally discrepant and therefore more interesting. With continued exposure to this pattern a more complete schema would form and it would become minimally discrepant. If this had happened by the time the later tests were conducted, this pattern would no longer be interesting.

There is an alternative theory concerning infant looking behaviour which would produce a different set of predictions for this type of experiment. Several writers have offered a model broadly based on Sokolov's (1963) explanation of orienting behaviour (Pancratz & Cohen, 1970, Friedman, 1972, Cohen, 1973). They propose that during a period of scanning the infant acquires some kind of representation, and it is a mismatch between the pattern and its representation which maintains looking. When an adequate representation has formed the two will match and the infant will look away.

In some respects this theory is similar to the discrepancy principle, but differs in one crucial aspect. When a new pattern is seen, the looking is 'open ended' since it will continue until a representation has formed. It is this assumption which the discrepancy principle rejects, since there are some patterns which are too discrepant and are only looked at for a short time. Looking away may occur for two reasons, while for the Sokolov approach there is only one. This would not predict a developmental preference for novelty unless an ad hoc assumption is introduced which maintains a slower rate of learning for younger infants.

Another possible explanation for the developmental preference for novelty is that visual perception requires a period for maturation, and it is only older infants who are capable of learning and showing attentional differences. Kagan (1971) has suggested that below 2 months infants will respond to stimulus properties such as contour and movement, but only react to discrepancy when older. There are several reasons why this proposal may not be useful, even though maturation does have a part to play. Studies of newborn children show that these infants will look less at a pattern when it is repeated over a series of trials and will look longer when it is replaced with a new one (Friedman et al., 1970)(Friedman, 1972). Infants as young as 60 hours will show such effects, and learning may begin almost as soon as the eyes are open.

It would seem premature for Kagan to reject the discrepancy principle for these younger infants without testing it directly. As the Greenberg et al. (1970) study shows, discrepancy effects may be detected at 2 months and there is no reason why experiments could not be carried out even earlier. If the argument put forward above is valid, the principle could explain the younger infant's dislike for novelty without altering the theory.

One final application of the discrepancy principle would be to explain the results in experiments concerned with infant memory. There are several techniques, but the basic method is to expose the infant to a standard pattern and record the decline in looking. To control for some other influence such as tiredness or boredom with the experiment as opposed to the establishment of a schema, a novel pattern is shown and the increase in looking recorded. Several demonstrations have been made of such behaviour (Caron and Caron, 1968, 1969, Schaffer and Parry, 1969). The decline of interest in a repeated pattern would be explained as the establishment of a schema which reduces the discrepancy. The subsequent increase in looking at a novel pattern would be due to the optimal amount of discrepancy produced by the existing schemata i.e. the preference for novelty.

A similar technique has been used to demonstrate the duration of a schema. Fagan (1970, 1971, 1973) has exposed infants to a pattern and then presented this standard paired with one which is novel. The schema established for the standard pattern renders it relatively un-interesting, and the novel one receives a significantly greater share of the looking. By testing with these pairs immediately after training and after delays, Fagan has shown the effects of learning to last for periods of 7 minutes, 2 hours and even 2 weeks. Again the discrepancy principle could account for such findings since it does not assume that forgetting will play a part in looking behaviour. While it may be felt that a theory of infant memory and learning should include a forgetting component, there has been almost no study of such infant behaviour. This is another area in which further research is needed.

5. Conclusions.

The discrepancy principle provides a means by which the length of a sequence of eye movements may be controlled. This is not the only determinant of looking for infants, and other influences such as movement, brightness, motivational status of the stimulus and level of arousal of the infant will also be involved (Kagan 1971). Despite these extra factors, discrepancy is important because it involves an interaction between memory and the stimulus, and so is directly relevant to the eye movement theory of perceptual development which is being developed.

When a pattern is too new or too familiar the infant will look away, but patterns which are partly new and partly familiar will receive the longest looks. This arrangement will operate during the establishment of a schema, and when a schema is being used to recognize a pattern.

The application of this principle to all stages of perceptual development means several predictions may be made about attentional behaviour. In the early stages when no schemata have formed, all patterns will be looked at for the same duration. However, those which have been seen before will be looked at longer when seen again than patterns which are completely new. Repeated presentation should reduce this effect as the patterns become well known and so not discrepant.

With more development this trend will reverse, and new patterns will be looked at more than ones which have been seen before. This will occur because of the development of schemata with which new patterns may interact. As a result, new patterns will tend to be optimally rather than extremely discrepant, and looks of an older infant at a pattern which is new will be much longer than those of the younger infant. Again, repeated presentation of a pattern will reduce the length of each look as a schema is formed and the pattern becomes minimally discrepant.

Finally, because of the preference for novelty, older infants will be able to distinguish patterns which they have seen before from those which are new by virtue of the amount of looking which each receives. This effect should be relatively permanent, and will still be exhibited after a delay.

CHAPTER 4.

THE COMPUTER MODEL: THE VISUAL WORLD, VISUAL PRE-PROCESSING AND OCULOMOTOR SYSTEM.

1. <u>The Technique of computer simulation.</u>

The theory which has been developed has several components, each of which is based on studies using different techniques and using different subjects. Although an attempt has been made to specify each component as clearly as possible, it is not certain that they will operate together in an integrated fashion. Often a theory which appears un-ambiguous may contain hidden inconsistencies when such an integration is attempted. The writing of a computer program provides a means by which such defects may be discovered.

This may come about in two ways. In order to write a program all the relevant parts must be set down explicitly. For example, a theory may make use of the concept of 'feature' without going into much detail about the nature of features, yet a program requires some definite statement to be made since it must operate with some kind of feature and not just a concept. Computer simulation thus serves to make explicit that in a theory which previously was implicit.

When a program has been written it is run on a computer. This permits observation of the theory 'in action' and will show whether the implications and predictions follow from the basic premises. It may be felt that if the details of all the separate components are known (which they must be in order to write the program), running the program will not tell us anything we did not know already. This is not always the case as it is the relations between the components which are revealed by the simulation, and there are no clear cut methods for deciding what these may be. One notable demonstration of this was a simulation of Hebb's neural theory of reverberating cell assemblies (Rochester et al., 1956). The initial attempt failed to produce regular patterns of firing as cell assemblies because the basic model was far too sensitive to even slight changes of input. Only when additional rules concerning the activity of neurones were introduced (in particular the inhibition of neurones as well as their excitation) did the predicted cell assemblies form.

A further advantage of computer simulation is that the program provides an exact description of the theory. This might be expected to confer on the theorist a means by which his theory may be communicated to others, but this advantage does not automatically follow. Programs can only be understood if the computing language is known, and even if this ability exists individual styles make it difficult for one programmer to understand another's work. An extra complication arises from the inclusion of material essential to the operation of the program but not part of the theory. This means that the program must be carefully documented so that the main routines are fully described and also the minor 'housekeeping' ones if they affect the main routines (Frijda, 1967). Several options are available here such as flow diagrams of the major stages involved which indicate what path ways of communication exists and the conditions under which each is followed. Working through examples of computation is another method which can be augmented by illustrations of the various transformations that occur during processing. The program description which follows includes all these options where appropriate, and a complete program listing with explanatory comments can be found in appendix 1.

These complications indicate that a computer model should not be treated as identical with a theory. Several writers have stressed this distinction - 'a model is an un-ambiguous formulation of a theory' (Frijda, 1967), 'models mediate between general theories and particular systems which the theories intend to explain' (Apter, 1970), 'simulation can serve to examine an existing theory' (Stelzl, 1971). These examples suggest that a computer simulation has something in common with more usual experimental procedures since both provide a situation in which the claims of a theory may be tested. While experimentation provides information which is primary in the sense that it is concerned with real rather than artificial behaviour, it may be helpful to regard the techniques of real-world experimentation and artificial world simulation as being at the opposite ends of a scale of experimental situations. Real-world experiments may also introduce considerable artificiality, for example the study of 'natural' animal behaviour in a laboratory setting. Simon (1969) has made a similar proposal with his idea of a science of the artificial.

The program description which follows is divided into several sections which correspond approximately with the theoretical discussions in the previous chapters. Where necessary, extra material from the relevant literature will be included to amplify certain points. The first section of this chapter describes the simulated environment within which the model operates, and this is followed by a section on visual processing based on neurophysiological data. This aspect has not been included yet, and is one example of a part of the theory which has to be made explicit before the program can operate. The remaining section describes the simulated oculomotor system. Chapter 5 will describe the structure of CYCLOPS' memory, and Chapter 6 will be concerned with the control of looking by means of the discrepancy principle.

2. Introduction to the program CYCLOPS.

CYCLOPS is a computer model of the perceptual development theory introduced in the first 3 chapters of this thesis. It consists of a single eye which moves about examining patterns presented in its visual world. CYCLOPS begins life with the ability to detect simple features such as edges and corners and to scan its world by means of 3 interacting oculomotor reflexes.

Initially CYCLOPS' memory is empty, but learning occurs quickly and schemata are established for the patterns which are scanned. As CYCLOPS acquires more visual experience it begins to show some of the developmental changes described for infants, such as an increasing preference for novelty. CYCLOPS may be imagined to be a one-eyed infant who spends his time constrained in a stimulus presentation apparatus of the kind described by Fantz and Nevis (1967).

3. The Visual World.

CYCLOPS operates within a square 2-dimensional area measuring 120 by 120 units. The size of a unit is arbitrary, but this measure serves to indicate the relative sizes of areas within the visual world (for example, the retina covers an area of 60 by 60 units or ¼ the total). This world contains 14,400 distinct points of 1 by 1 units, each of which may be in one of two states. These states are 1 or 0 and correspond to white and black, the visual world providing a black background onto which white patterns are projected. This basic division into two levels of brightness was chosen for simplicity, but there is no reason why other states could not be used, corresponding with shades of gray or different colours. An earlier version of CYCLOPS included this option, but all the experiments reported in the following chapters used the simpler white/black patterns. Figure 5 shows the visual world with the retina covering a region near the top left-hand corner.

All patterns have edges which are straight and oriented vertically or horizontally. Curves and diagonals are not included, and there are no detectors in the simulated visual cortex which could process such edges. The reason for this simplification was to cut down on the running time of the program and prevent the experiments becoming too lengthy and expensive. Despite this limitation a variety of patterns were constructed, and the complete library is shown in outline in figures 6, 7 and 8. Most can be fitted inside a square measuring 30 by 30 units though some larger patterns were used. There were no particular rules for construction except the requirement that they all be different. Some contain internal details or 'holes', some extend more vertically than horizontally, and the influences of these variations on CYCLOPS will be considered later.

Patterns may be placed anywhere within the visual world

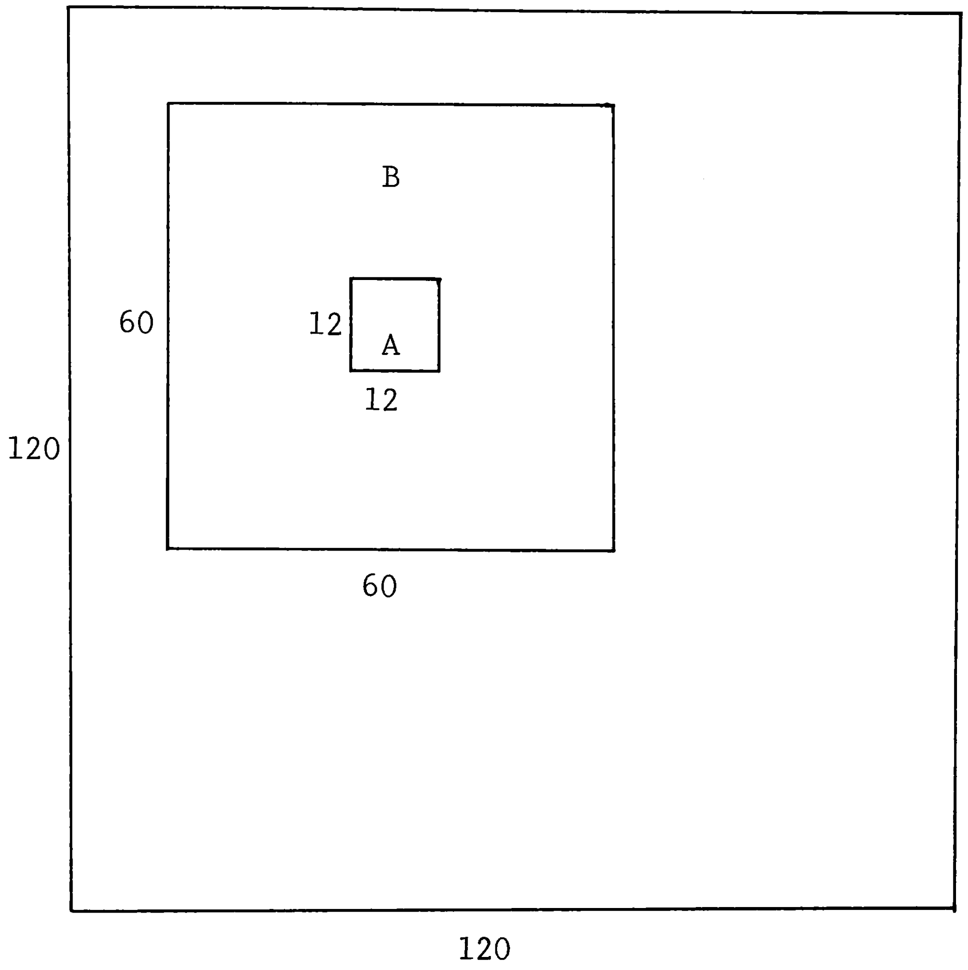


Figure 5. Visual World of 120 by 120 units. The retina in the top left-hand corner measures 60 by 60 units. Region B is the periphery, region A is the fovea.

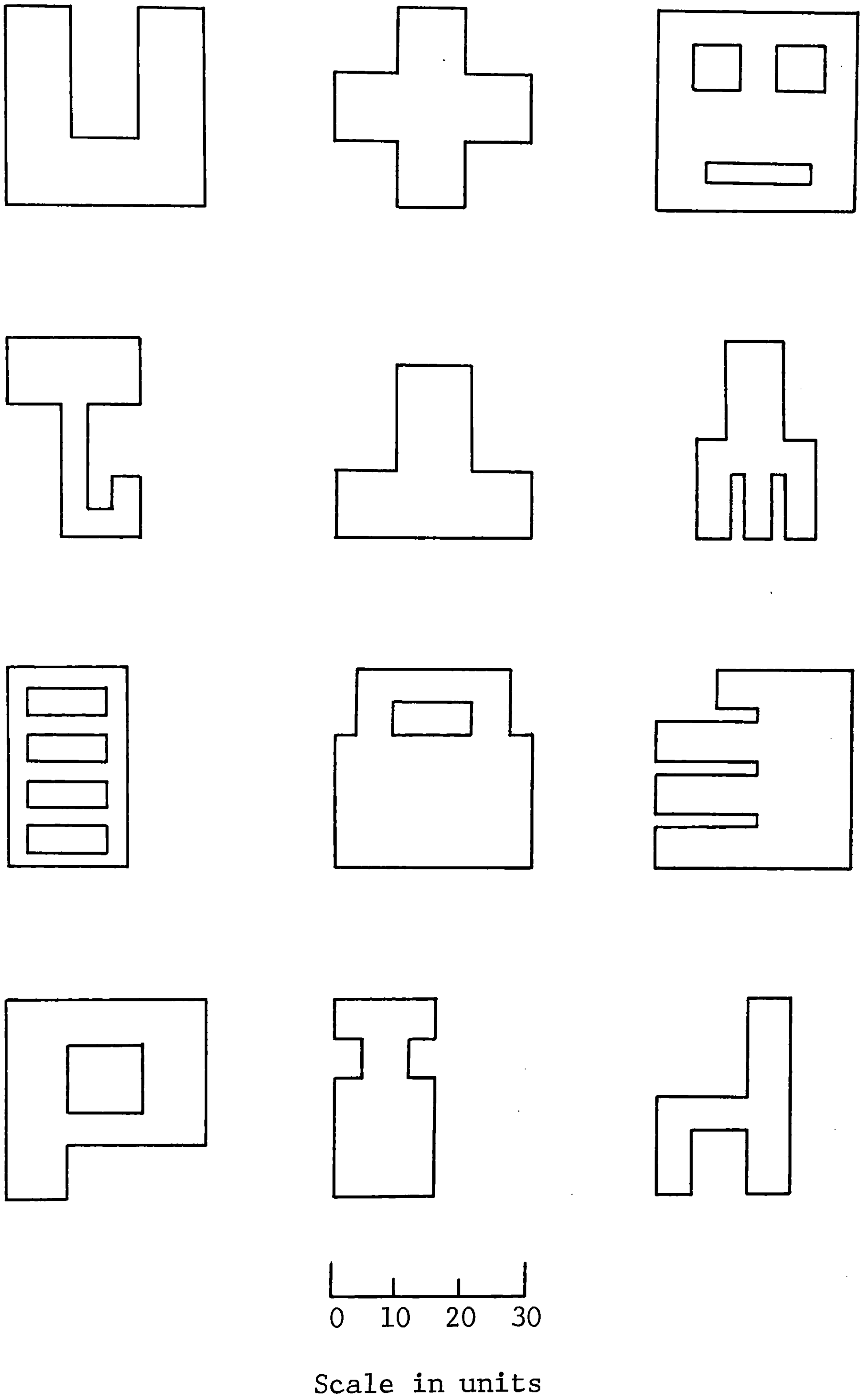


Figure 6. CYCLOPS' pattern library.

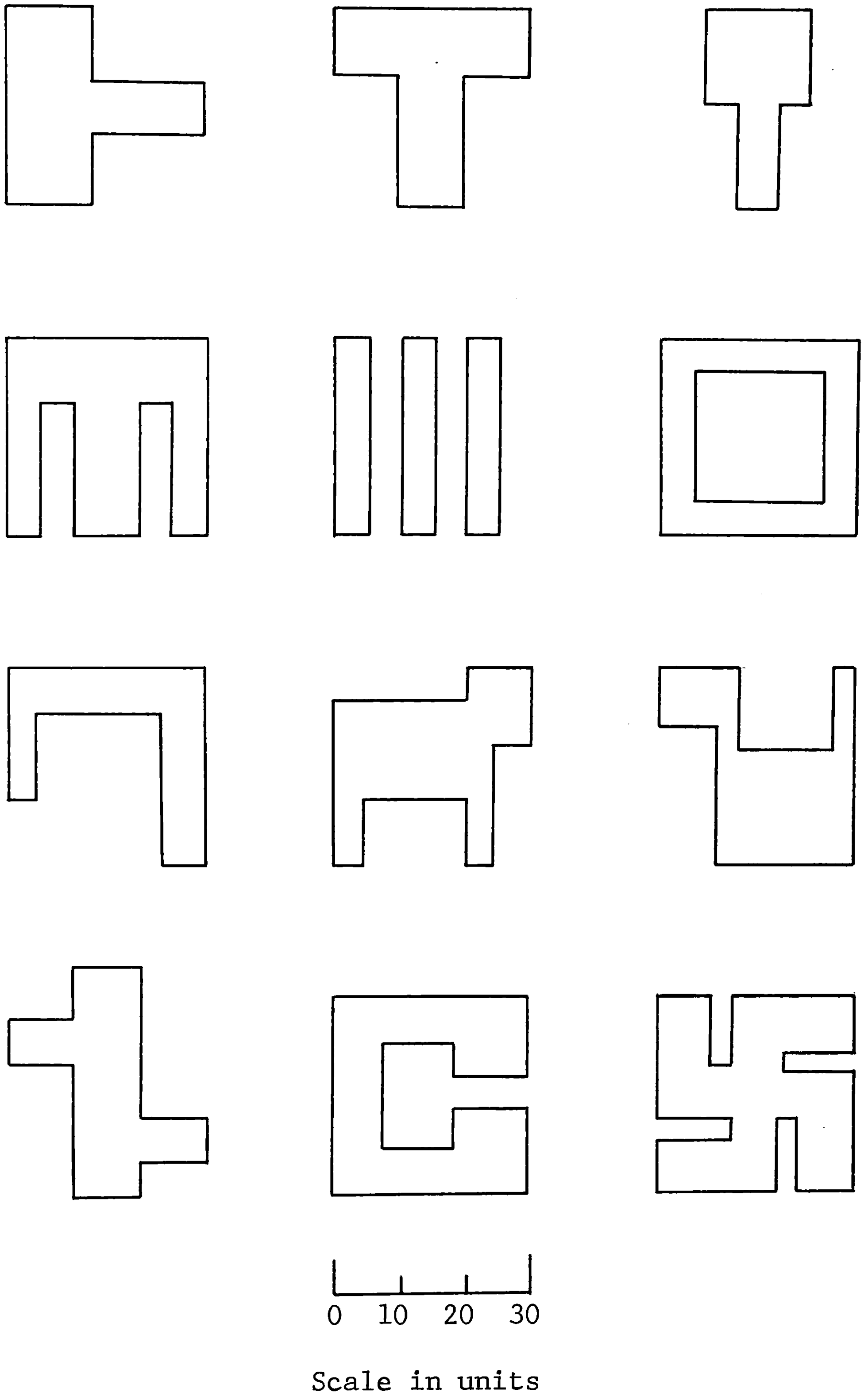


Figure 7. CYCLOPS' pattern library.

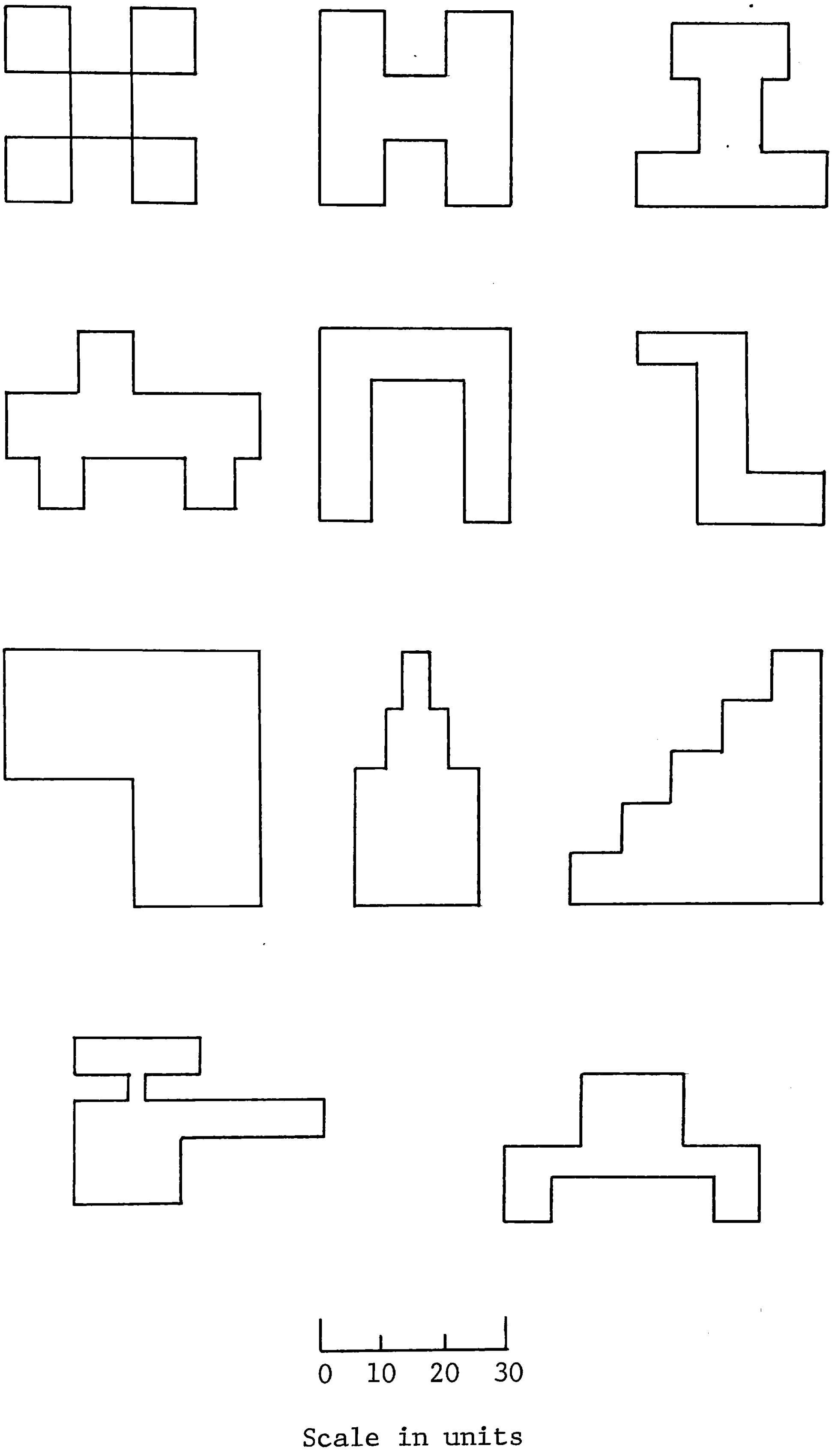


Figure 8. CYCLOPS' pattern library.

and at any time while the program is running. They may be displaced vertically or horizontally, but cannot be rotated. There are no restrictions on how close patterns may be placed to each other, but overlapping patterns will merge together to form a composite. Patterns may be removed from any region, and the routine which performs this operation allows either for the whole or specified parts to be deleted. This facility is useful for deforming patterns in various ways in experiments on the effects of discrepancy. There are no restrictions save available space on the number of patterns which may be placed in the visual world at any time, but generally no more than two have been used together, depending on the experimental design.

4. Visual pre-processing.

a. The fovea.

CYCLOPS is equipped with a retina measuring 60 by 60 units, of which a central square region of 12 by 12 units is occupied by the fovea (see Figure 5). The fovea contains 144 cells, each of which covers a 1 by 1 unit region of the visual world. These cells correspond with the cones of mammalian central vision, and though vastly reduced in number are sufficient to supply CYCLOPS with detailed vision.

The foveal cells represent the first stage of a hierarchical processing system which detects the features located in the region of visual world covered by the fovea.

Each cell assumes the state of the region of visual world it covers, producing an exact copy.

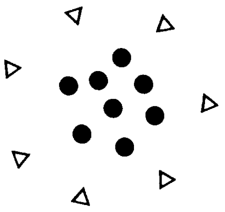
b. Ganglion and lateral geniculate cells.

The basic input from the fovea is subjected to successive levels of processing, each level becoming the input for the next. Visual pre-processing takes the form of a layered computer (Sutro and McCulloch, 1969), and the design of each layer is based on the neurophysiological findings of Hubel and Wiesel (1962 and 1965).

The second level of processing is concerned with detecting regions of contrast on the fovea. While there is evidence for the detection of more complex features at this level such as edges, orientation and movement (Lettvin et al., 1959, Michael, 1969), some species such as the cat (Hubel and Wiesel, 1961) and monkey (Hubel and Wiesel, 1968) respond only to contour and reserve the detection of more complex features for the cortex. This latter approach is adopted here.

Recordings from ganglion cells in the retina show that each is responsive to stimulation in only a small area, the receptive field (Kuffler, 1953, Wiesel, 1960). These fields are circular and contain two antagonistic concentric regions which may be either excitatory or inhibitory. Fields are described as on centered or off centered according to the status of the central region, and Figure 9 illustrates both types.

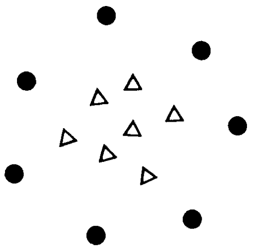
These antagonistic areas oppose each other so that



a. On centered concentric ganglion cell field.

● excitatory region.

△ inhibitory region.



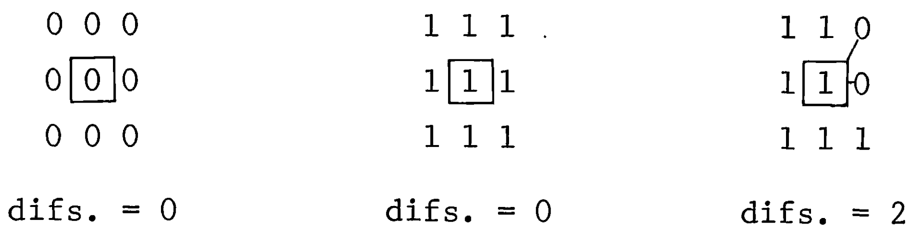
b. Off centered concentric ganglion cell field.

Figure 9. Concentric ganglion cell fields (re-drawn from Hubel & Wiesel, 1962).

stimulation of the whole field yields a weak response from the cell. Ganglion cells tend to respond according to the nature of their central region with this kind of stimulation, but lateral geniculate cells are more effectively suppressed by the antagonistic surround. Since the two types of cell are so similar, no distinction is made in CYCLOPS and contour detection occurs at a single level.

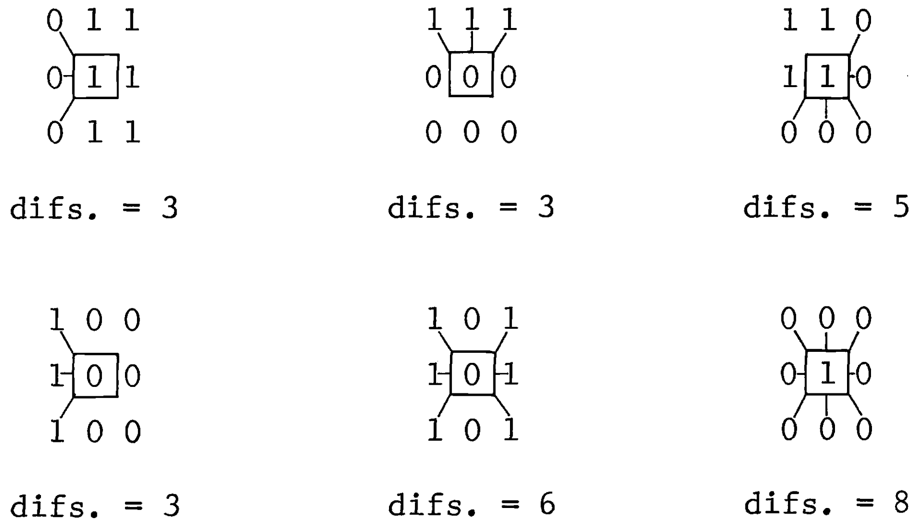
These cells by virtue of the design of their fields, respond best when there is a contrast within the receptive field and thus act as contour detectors. CYCLOPS has ganglion cells with fields containing 9 foveal cells, arranged in a 3 by 3 square. These fields overlap within the 12 by 12 fovea, forming a 10 by 10 array of 100 of separate fields. The ganglion cell array contains 100 cells, each receiving the output from one of the fields.

The central cell in the ganglion cell field is antagonistic to the 8 in the surround, and a count is made of the number of differences between the state of the central cell and those in the surround. The outcome of this count may vary from 0 to a maximum of 8, and the ganglion cell is only allowed to fire if the total number of differences is 3 or more. The action of this field is both on and off centered because it does not matter whether the central cell is in state 1 or 0. Figures 10a and 10b give examples of patterns of stimulation which will inhibit



difs. = 0 difs. = 0 difs. = 2

a. None of these configurations will fire the ganglion cell. The number of Central/surround differences shown below each configuration.



difs. = 3 difs. = 3 difs. = 5

difs. = 3 difs. = 6 difs. = 8

b. All of these configurations will fire the ganglion cell.

Figure 10. Stimulus configurations and simulated ganglion cell fields.

or permit the ganglion cell to fire. When a cell does fire, its state is set to 1, and when inhibited it is set to 0.

It is interesting that fields of this nature produce a double 'band' of activity wherever a contour is located. On one side of the contour the ganglion cells act in an on centered fashion, while on the other they are off centered. If the mammalian retina also acts in this way, the two types of field would co-operate to produce a strong response at the site of a contour. Figure 11 illustrates this for an 'L' shaped pattern of foveal stimulation.

The cells in the ganglion cell array are arranged in a 10 by 10 square, which is smaller than the fovea. This is the largest number of ganglion cell fields which can be completely fitted onto the fovea. These fields overlap maximally, which is also a feature of mammalian fields (Horridge, 1968). It means that each cell will be either excitatory or inhibitory depending on its position within a field. This variety is probably achieved by specific interneurones to produce the lateral inhibition within each field (Horridge, 1968, Ratliff, 1965, Werblin, 1973), and these neural connections are simulated in CYCLOPS by the routine which counts the differences within a field.

Similar types of fields have been used elsewhere in simulations of visual processing. Zinser (1970) described a 'spot Operator' which had a field of 5 by 5 units,

1	1	1	1	1	1	1	0	0	0	0	0
1	1	1	1	1	1	1	0	0	0	0	0
1	1	1	1	1	1	1	0	0	0	0	0
1	1	1	1	1	1	1	0	0	0	0	0
1	1	1	1	1	1	1	0	0	0	0	0
1	1	1	1	1	1	1	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1

a. Pattern of stimulation falling on the fovea

0	0	0	0	0	1	1	0	0	0
0	0	0	0	0	1	1	0	0	0
0	0	0	0	0	1	1	0	0	0
0	0	0	0	0	1	1	0	0	0
0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

b. Resultant pattern of activity in ganglion cell array. Only those cells fire whose fields cover a region of contour.

Figure 11. Detection of contour by ganglion cells.

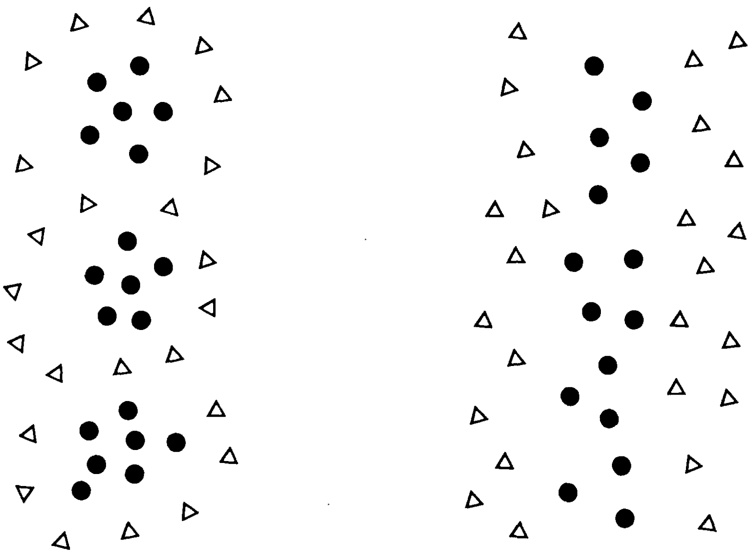
representing the excitatory centre but not the inhibitory surround. Each cell within the field was given a weighting value, and those in the centre had a higher value than those in the periphery. These were multiplied by the values of the pattern cells which they covered, and the ganglion cell fired only if the total was more than some threshold value. While this scheme would detect contour, it is only a partial simulation since a diffusely stimulated field would produce maximal stimulation and cause the cell to fire.

Sutro and McCulloch (1969) describe a diamond-shaped weighting function which did have an excitatory centre and inhibitory surround. Each central cell contributed a positive score to the total when stimulated, and each peripheral cell contributed a negative score. This function essentially computes the differences like CYCLOPS and would not respond to diffuse stimulation. Only the on centered fields were simulated, and the authors report that the function would produce Mach band effects when applied to a series of stimulus bands representing shades of gray. A similar type of function was also used by Fukushima (1970), but again the off centered version was not included.

c. Simple cortical cells.

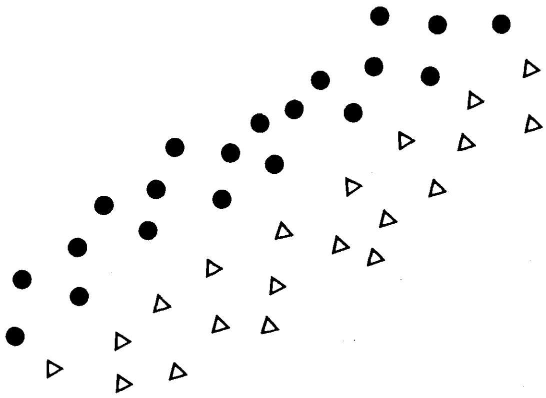
The next level of processing described by Hubel and Wiesel (1962) is located in the visual cortex. The cells here have fields which are oblong and contain antagonistic excitatory and inhibitory regions. These cells are highly selective over the kind of stimulation which will cause them to fire. The effective stimuli can be described as slits, edges and dark bars, and often a moving stimulus is preferred. It is essential for these linear stimuli to have the correct orientation to fire the cell, otherwise it is inhibited. Figures 12b and 12c show two kinds of simple cortical fields, each for a different orientation. Only stimulation falling on the excitatory regions will be effective as the ability of the inhibitory regions to prevent the cortical cell firing is considerable.

Simple cortical cells all receive connections from the lateral geniculate cells, and it has been suggested that a simple linear arrangement of lateral geniculate fields will account for the simple cortical properties (Hubel and Wiesel, 1965). An example is shown in figures 12a and 12b where the combination of on centered lateral geniculate fields produces the linear regions of excitation and inhibition within the simple cortical field. This kind arrangement could not account for the simple cortical field shown in figure 12c, and it is more likely that both excitatory and inhibitory regions contain many lateral geniculate cells which can be on or off centered. While all lateral geniculate cells respond positively to contour, some would have an inhibitory role in the simple cortical



a. Possible arrangement of ganglion cell fields

b. Simple cortical cell field which might result from arrangement in a.



c. No simple arrangement of ganglion cell fields could account for this simple cell field.

Figure 12. Possible construction of simple cortical cell fields. Re-drawn from Hubel & Wiesel (1962) and (1965). ● excitatory region. △ inhibitory region.

fields.

Although each simple cortical cell has a field with a particular orientation, a great number of different orientations have been discovered. The cortex maintains a strict organization of these different cells by confining those with the same orientation with a column (Hubel 1963, Hubel and Wiesel, 1965). All the cells in a column have fields located approximately on the same area of retina, but each such area will be represented many times over in the cortex with a different field orientation depending on the column of cells.

In CYCLOPS there are only fields with two orientations. Vertical fields receive input from 20 ganglion cells, arranged in 4 columns of 5 cells each. The two central columns are excitatory and the two outer columns are inhibitory. Horizontal fields are similar except the 20 cells are arranged in 4 rows of 5 cells each (see figure 13a and 13b). The design of these fields corresponds with one experimental finding reported by Hubel and Wiesel (1962, P.265, figure 2c), which is reproduced in a vertical orientation in figure 9b. Similar schemes were also adopted by Zinser (1970) and Fukushima (1970). This was chosen because of the double column or row of excitatory cells in

```
- + + -
- + + -
- + + -
- + + -
- + + -
```

a. Vertically oriented simple cortical field. Each sign indicates a ganglion/lateral geniculate cell, + excitatory, - inhibitory.

```
- - - - -
+ + + + +
+ + + + +
- - - - -
```

b. Horizontally oriented simple cortical field.

Figure 13. Simulated simple cortical fields

in the centre of the field corresponds well with the double band of ganglion cell activity which a contour produces.

A simple cortical cell fires if the sum of the active excitatory cells minus the sum of the active inhibitory cells in its field is 6 or more. Any score less than this threshold will inhibit the cell and it is set to 0. Examples of ganglion cell activity which inhibit these cells are shown in figure 14a, while those which fire the cells are shown in figure 14b.

There is a total of 48 cells of each orientation, and the fields may be likened to a window which is applied repeatedly over the whole ganglion cell array. These fields overlap, and a ganglion cell may belong in a vertical or horizontal cortical cell field, and may be excitatory or inhibitory.

d. Complex cortical cells.

The cortex contains other cell types which respond to the same kinds of stimuli as simple cells, but their fields do not contain any inhibitory regions. These complex fields are larger than the simple ones, and the conclusion is that they contain several component simple cells (Hubel and Wiesel, 1965). The structure of the cortex supports this interpretation as the columns contain those simple cells which are found in the field of a complex cell. The purpose of such cells would seem to be to produce a uniform response despite positional variations introduced by slight eye

1 0 0 0	0 0 0 0
1 0 0 0	0 0 0 0
1 0 0 0	1 1 1 1
1 0 0 0	1 1 1 1
1 0 0 0	0 0 0 0

Vertical fields

0 0 0 0 0	0 0 1 1 0
0 0 0 0 0	0 0 1 1 0
0 0 0 0 0	0 0 1 1 0
1 1 1 1 1	0 0 1 1 0

Horizontal fields

a. None of these configurations will fire the cell.

0 1 1 0	
0 1 1 0	0 0 0 0 0
0 1 1 0	1 1 1 1 1
0 1 1 0	1 1 1 1 1
0 1 1 0	0 0 0 0 0
Vertical field	Horizontal field

b. These configurations will fire the cell.

Figure 14. Ganglion cell activity and simulated simple cortical cell fields.

movements, and in addition they serve to reduce the amount of information which higher levels of the cortex will process.

CYCLOPS contains complex cells for both these reasons, and the design of the vertical and horizontal fields is shown in figures 15 and 16. Each complex cell contains only two simple cells within its field, and these fields do not overlap. The two arrays of simple cells are reduced to arrays of 24 complex cells (figures 15 and 16). For the vertical cells, adjacent pairs of simple cells across columns are examined, and the complex cell fires if either of those in its field are active. For horizontal cells, the pairing is made within columns. Because each complex cell field contains 2 simple cells within its field, and the complex fields do not overlap, each complex cell array contains only half the number of cells in the corresponding simple cell array.

e. Hypercomplex cells.

These cells have been detected in higher levels of the cortex (areas 18 and 19). They respond to stimuli with more than one contour orientation and so differ from simple and complex cells. Edges and corners fire these cells, and their fields contain excitatory and inhibitory regions. At an even higher level are cells which could be explained as combinations of hypercomplex cells because orientations are

0 0 0 0 1 0 0 0

0 0 0 0 1 0 0 0

0 0 0 0 1 0 0 0

0 0 0 0 1 0 0 0

0 0 0 0 1 0 0 0

|0 0| |0 0| |1 0| |0 0|

A B C D

Vertical simple cortical cell array.

Letters A-D indicate the pairs of cells within each complex cell field.

+	+

Vertical Complex cortical cell field

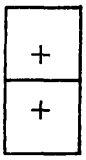
A	B	C	D
0	0	1	0
0	0	1	0
0	0	1	0
0	0	1	0
0	0	1	0
0	0	1	0

Resulting vertical complex cortical cell array. complex fields do not overlap, and each column in this array is derived from 2 columns in the simple cell array.

Figure 15. Vertical complex cortical cells.

0	0	0	0	0	0	A
0	0	0	0	0	0	
0	0	0	0	0	0	B
1	1	1	1	1	1	
0	0	0	0	0	0	C
0	0	0	0	0	0	
0	0	0	0	0	0	D
0	0	0	0	0	0	

Horizontal simple cortical cell array. Letters A-D indicate the pairs of cells within each complex cell field.



Horizontal complex cell field

0	0	0	0	0	0	A
1	1	1	1	1	1	B
0	0	0	0	0	0	C
0	0	0	0	0	0	D

Resulting horizontal complex cortical cell array. Complex fields do not overlap and each row in this array is derived from 2 rows in the simple cell array.

Figure. 16 Horizontal complex cortical cells.

combined, and the positioning of the stimulus does not affect response (Hubel and Wiesel, 1965, 1968).

The plausible explanation of the structure of these fields is that they are made up of complex cells with the aim of detecting corners and curves rather than linear segments. CYCLOPS has 4 arrays of hypercomplex cells, each detecting a different type of stopped contour. A vertical section of contour may be stopped at the top (figure 17a) or at the bottom (figure 17b.) This may be due to a corner or a tongue as the illustrations show. The hypercomplex field which detects a vertical edge stopped at the top is shown in figure 17c, and the one which detects a vertical edge stopped at the bottom is shown in figure 17d. These fields are applied to the vertical complex cell array and are permitted to overlap. The hypercomplex cell will only fire if the cell in the excitatory part of the field is active and the cell in the inhibitory part inactive. If this is the case, the cell in the hypercomplex array is set to 1, otherwise it is set to 0. The kinds of contours which will inhibit the vertical hypercomplex cells are shown in figure 17e, and some which will activate the cell are shown in figure 17f.

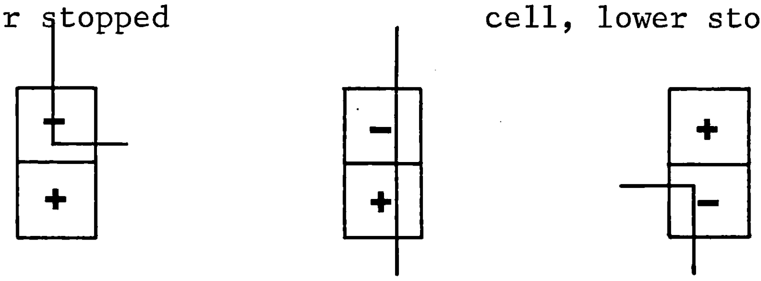
The horizontal hypercomplex fields are similar, and are shown with horizontal edges stopped at the left or right in figures 18a - 18d. The size of the array of each type of hypercomplex cell is 20 cells, arranged in 4 columns of 5

a. Vertical contours stopped at the top.

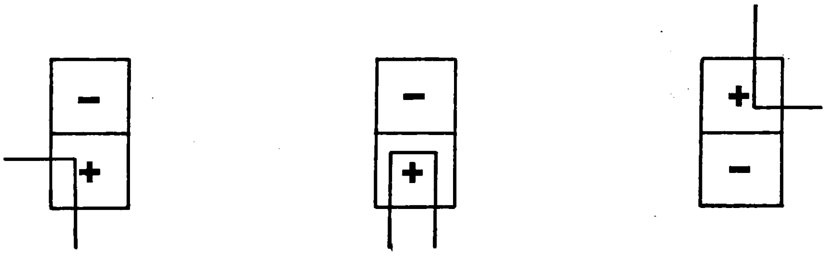
b. Vertical contours stopped at the bottom.

c. Receptive field for vertical hypercomplex cell, upper stopped

d. Receptive field for vertical hypercomplex cell, lower stopped.



e. None of these edges will cause the cell to fire.



f. All these edges will cause the cell to fire.

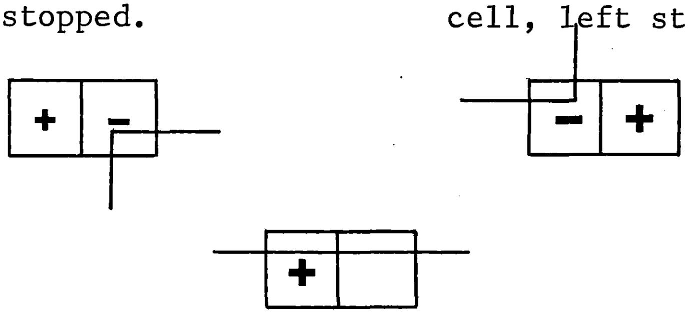
Figure 17. Vertical hypercomplex cells.

a. Horizontal contours stopped at the right

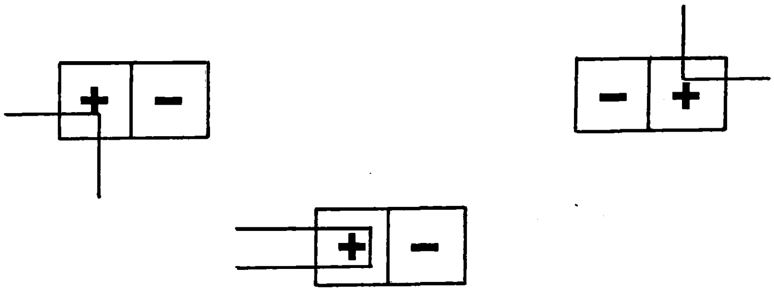
b. Horizontal contours stopped at the left

c. Receptive field for horizontal hypercomplex cell, right stopped.

d. Receptive field for horizontal hypercomplex cell, left stopped.



e. None of these edges will cause the cell to fire.



f. All these edges will cause the cell to fire.

Figure 18. Horizontal hypercomplex cells.

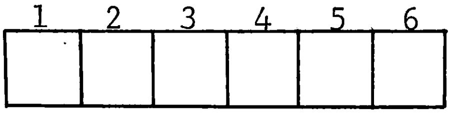
cells for the vertical types, and vice - versa for the horizontal. Patterns of stimulation which inhibit or activate these horizontal hypercomplex cells are shown in figures 18e and 18f.

f. Detection of features.

Hypercomplex cells are the highest level of processing pursued by CYCLOPS, and by this stage the pattern of stimulation on the fovea has been broken down into a number of distinct features. The array of foveal cells copies the pattern falling on it, and the successive levels of processing reduce this pattern to a few active cells, each representing a pattern section in a highly condensed form. This compression of information has been likened to a grammar which transforms the pattern by application of 'rewriting' rules at each level of the hierarchy (Clowes, 1967). Figures 20 and 21 illustrate the several levels of processing.

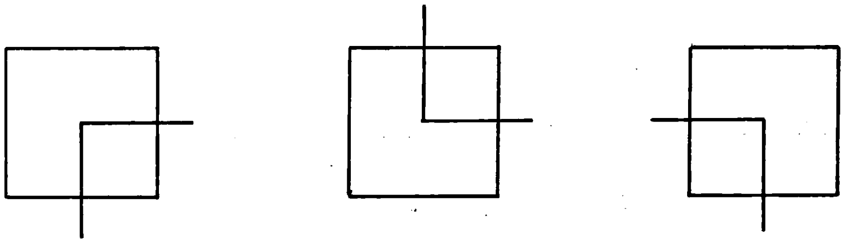
The features detected at each level are combined in a list which describes for CYCLOPS the pattern of foveal stimulation. There is very little neurophysiological data about this process in the brain, and it is not certain if any of the levels discovered contribute directly to perception or whether further processing occurs. It has been suggested that the spatial relations between the various features should be recorded, and schemes of varying ability have been proposed to achieve this (Wallingford, 1972, Sutherland, 1968, Clowes, 1967, 1969, 1971). It was decided not to attempt to spatially relate the features detected with one fixation as this was felt to be an unnecessary procedure. The above examples (Wallingford,) etc., are concerned with processing a whole pattern, while CYCLOPS only detects features within the small region covered by the fovea. As figure 19 shows, the list of cortically detected features contained within the fovea can distinguish between quite similar patterns of stimulation (eg. different types of corners). The task of relating these clusters of features with each other will be achieved by eye movements.

The foveal feature list (FFL) has 6 entries representing the activity in the complex and hypercomplex cell arrays. The first entry is for the vertical complex cells, and records the number of columns in the array which contain active cells. An entry of 0 indicates there are no vertical contours. An entry of 1 indicates one vertical contour, while entries of 2 or 3 mean there are several contours in parallel. The second entry in the foveal feature list is for the horizontal complex cells and indicates the number of rows containing active cells. The remaining 4 entries are reserved for the 4 types of hypercomplex cell, and here the total number of



Foveal feature list.

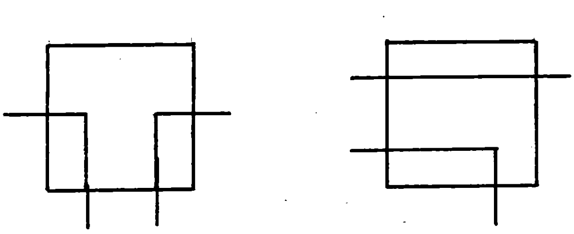
1. Vertical complex
2. Horizontal complex
3. Vertical hypercomplex, lower stopped
4. Vertical hypercomplex, upper stopped
5. Horizontal hypercomplex, left stopped
6. Horizontal hypercomplex, right stopped



FFL
1 1 0 1 1 0

FFL
1 1 1 0 1 0

FFL
1 1 0 1 0 1



FFL
2 0 0 0 0 0

FFL
2 2 0 2 1 1

FFL
1 2 0 1 0 1

Limits of the fovea indicated by the square.

Figure 19. Foveal feature lists and patterns of stimulation.

```
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 1 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 1 1 1 0 0
```

Pattern of stimulation falling on the fovea.

```
0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0
0 0 0 1 1 1 1 1 0 0
0 0 1 1 1 1 1 1 1 0
0 1 1 0 0 0 0 0 1 1
0 1 1 0 0 0 0 0 1 1
0 1 1 0 0 0 0 0 1 1
0 1 1 0 0 0 0 0 1 1
0 1 1 0 0 0 0 0 1 1
0 1 1 0 0 0 0 0 1 1
```

Activity in ganglion cell array.

```
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
1 0 0 0 0 0 0 1
1 0 0 0 0 0 0 1
1 0 0 0 0 0 0 1
```

Vertical simple cortical cell array.

```
0 0 0 0 0 0
0 0 1 1 1 0
0 0 0 0 0 0
0 0 0 0 0 0
0 0 0 0 0 0
0 0 0 0 0 0
0 0 0 0 0 0
0 0 0 0 0 0
```

Horizontal simple cortical cell array.

Figure 20. Pattern processing - fovea to cortex.

```
0 0 0 0
0 0 0 0
0 0 0 0
1 0 0 1
1 0 0 1
1 0 0 1
```

1. Vertical complex cortical cell array.

```
0 0 1 1 1 0
0 0 0 0 0 0
0 0 0 0 0 0
0 0 0 0 0 0
```

2. Horizontal complex cortical cell array.

```
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
```

3. Vertical hypercomplex lower stopped array.

```
0 1 0 0 0
0 0 0 0 0
0 0 0 0 0
0 0 0 0 0
```

5. Horizontal hypercomplex, left stopped array.

```
0 0 0 0
0 0 0 0
1 0 0 1
0 0 0 0
0 0 0 0
```

4. Vertical hypercomplex, upper stopped array.

```
0 0 0 0 1
0 0 0 0 0
0 0 0 0 0
0 0 0 0 0
```

6. Horizontal hypercomplex, right stopped array.

Foveal Feature List

1	2	3	4	5	6
2	1	0	2	1	1

Figure 21. Pattern processing - higher levels of the cortex.

active cells in any of these arrays is recorded.

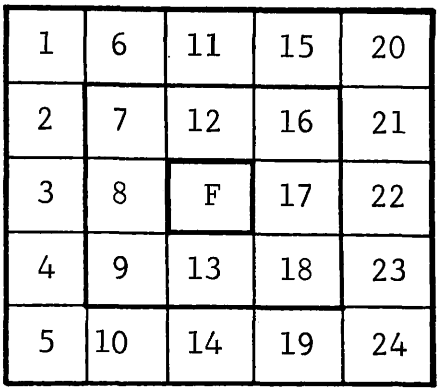
g. The peripheral retina.

In contrast to the detail which the fovea processes, the peripheral retina of CYCLOPS has a limited capacity. All the types of cells mentioned so far have been found with receptive fields in the peripheral retina as well as the fovea or area of central vision (Wiesel, 1960, Hubel and Wiesel, 1962, 1965). Generally, peripheral fields are much larger than central ones, and increase in size the further away from the centre they are located. For example, circular ganglion cell fields in the periphery have centres 64 times as large as those in the area centralis of the cat retina (Wiesel, 1960). This would reflect the different role of peripheral vision in detecting a stimulus rather than identifying it, since a stimulus would readily fire such a cell, but many different kinds of stimuli would produce the same response.

Although such large fields alone would make accurate location of a peripheral stimulus impossible, the concept of distributed motor control (Arbib, 1972) suggests that the combined operation of such fields could overcome this disadvantage. No matter what the size, providing the fields overlapped, a stimulus would produce a specific pattern of activity depending on its location. Such a scheme was considered for CYCLOPS so that the peripheral retina would have a similar structure as the fovea, but computational problems required an alternative. The peripheral fields would take too long to process since their combined area is 24 times that of the fovea.

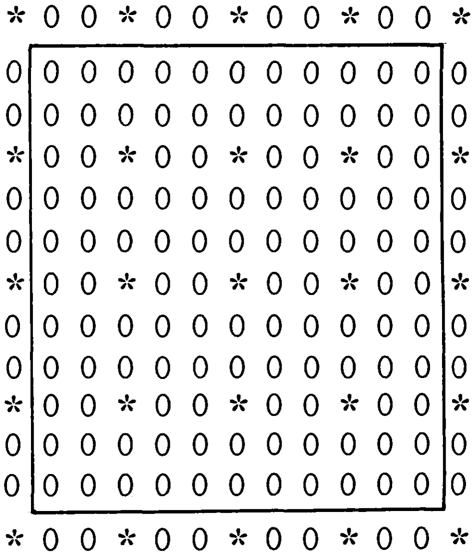
The peripheral retina of CYCLOPS is designed with the specific function of detecting the presence and approximate location of stimuli, but not to detect the features. The periphery measures 60 by 60 units except for a central portion of 12 by 12 units which is the fovea. This peripheral retina is divided into 24 fields of 13 by 13 units which overlap by 1 unit. The fovea is surrounded by 2 rings of peripheral fields, an inner ring of 8 fields and an outer ring of 16 (see figure 22a). A similar arrangement was used by Gyr et al (1966), though only the inner ring of 8 was used.

Cells in a peripheral field behave like those in the fovea since they assume the state of the particular region of the visual world which they cover. Contour is detected within a field by examining only 25 of the constituent 169 cells. (figure 22b). If at least 5 of these cells are active (state = 1) and 5 are not active (state = 0), the field will register contour. This is recorded in a list of 24 entries, one per field, which may be set to 0 (no contour) or 1 (contour detected). This scheme means that any field which is diffusely stimulated or not stimulated at all will not



1	6	11	15	20
2	7	12	16	21
3	8	F	17	22
4	9	13	18	23
5	10	14	19	24

a. 24 peripheral fields. The region marked 'F' is the fovea, the inner and outer rings are shown in heavier outline. Each field is 12 by 12 units.



```
* 0 0 * 0 0 * 0 0 * 0 0 *
0|0 0 0 0 0 0 0 0 0 0 0|0
0|0 0 0 0 0 0 0 0 0 0 0|0
*|0 0 * 0 0 * 0 0 * 0 0|*
0|0 0 0 0 0 0 0 0 0 0 0|0
0|0 0 0 0 0 0 0 0 0 0 0|0
*|0 0 * 0 0 * 0 0 * 0 0|*
0|0 0 0 0 0 0 0 0 0 0 0|0
0|0 0 0 0 0 0 0 0 0 0 0|0
*|0 0 * 0 0 * 0 0 * 0 0|*
0|0 0 0 0 0 0 0 0 0 0 0|0
0|0 0 0 0 0 0 0 0 0 0 0|0
* 0 0 * 0 0 * 0 0 * 0 0 *
```

b. 13 by 13 cells within a peripheral field. Those marked as * are the only ones which are examined. At least 5 must have value 1 and 5 must have value 0 if a contour is to be detected. Those cells outside the boundary are shared by other fields.

Figure 22. Peripheral retinal fields.

indicate the presence of contour. This explains the field overlap of 1 unit, for without it a contour located exactly on the boundary of two fields would not be detected by either.

Although this is a highly simplified scheme, the routine works quickly and successfully, detecting contours and producing a list of active regions.

5. The oculomotor system.

CYCLOPS has three different oculomotor reflexes, each serving a different function. The saccadic reflex operates to shift the position of the fovea while a pattern is being scanned, producing a series of eye movements which are aimed at specific targets. The foveal centering reflex executes small, 'corrective' eye movements after a saccade has been made in order to bring the contours detected on the fovea to a central position. Finally, the blind move reflex operates when a series of fixations is ended, and the fovea is moved away from the pattern which was scanned. This reflex also moves the eye about the visual world to find something new to fixate.

Whenever any of these oculomotor reflexes operates, the peripheral retina is allowed to move outside the boundary of the visual world, but the fovea is constrained and may never exceed this limit. When this happens, the peripheral retina will not register any contour outside the visual world, nor at the point where the boundary is crossed.

a. The saccadic reflex.

The peripheral retina indicates a number of different regions where contour is located, and each competes with the others to become a target for fixation. In this situation, it is the combined influence of all these regions which decides which is to become the target. Because the retina is 2-dimensional there are 2 possible axes for a movement. Within each there are 2 directions - up or down and left or right. Each peripheral region which is active may contribute to a 'pull' in one or more of these directions. The first stage in choosing a target is to count the number of regions pulling in each direction. Since a move cannot be made in both directions along one axis, the largest of these antagonistic pulls is selected for each axis. If it happens that an antagonistic pair of directions have equal pulls, the effect is to cancel both out and neither is selected. However, it could happen that a balance for all 4 directions occurs, so to prevent CYCLOPS becoming completely stuck a region containing contour would be chosen randomly to eliminate this deadlock.

Using this method, information from the number of active regions is used to obtain the direction of the eye movement which may be considered as the resultant of each individual pull. It will be recalled that Pitts and McCulloch (1947) devised a similar scheme with their model of the colliculus, though areas of brightness were the effective stimuli. In that model it was the centre of gravity of a pattern which was fixated, while for CYCLOPS this is prevented by making the pulls in opposite directions mutually exclusive, and further by using the contours of a pattern to guide fixation.

Once the direction of a movement is obtained for each axis, the sizes of these components must be determined. An examination of figure 22a will show that there are 2 sizes of movement possible in any direction, one of 12 units and the other of 24. For each direction, a count is made of the number of active peripheral regions at both of these distances from the fovea, there being a maximum of 5 for either size. The one which is larger is selected, but if they should be equal, the smaller distance is arbitrarily chosen.

When both the sizes and directions of the movements along the two axes are known, the peripheral target has been specified and the eye movement can be executed. One further check is made to ensure that the peripheral region chosen does indicate the presence of contour, since some unusual configurations may cause an inactive region to be selected. If it should be the case that the target region selected does not indicate any contour, this target is rejected and one is chosen randomly from among the other active regions. Although this is a weak point in the system because of its ad hoc nature, it should be stressed that it is only rarely that such a target must be selected randomly. This means that effectively there is little need to include this component in the program, but because it is impossible to forsee all conditions which might arise it was retained to ensure smooth operation. Following this precautionary check, the eye movement is executed by altering the co-ordinates of the retina to bring the target region onto the fovea.

A series of eye movements is made when a pattern is seen, and each is computed in this fashion. Early tests soon revealed one annoying tendency to make an alternating series of movements between only two regions, greatly reducing the exploration and learning of patterns. To prevent this and encourage longer fixation series, a simple addition was made to the routine. Following an eye movement, the peripheral region which was previously fixated is set to 0. This means that this region will never be chosen as a target on the following fixation, though it will be available later on in the series. This simple rule prevents the alternating fixations of the earlier model.

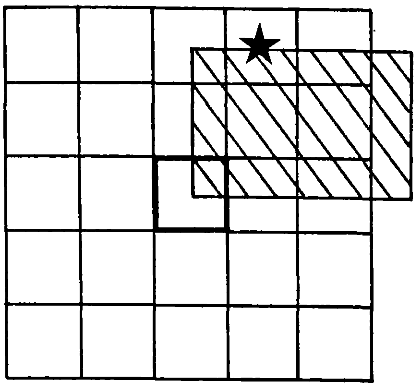
A series of fixations on a pattern is shown in figure

23, and the computation which determines the first target region of this series is illustrated in figure 24. Figure 25 shows the pattern of peripheral activity which occurs at each stage in the series.

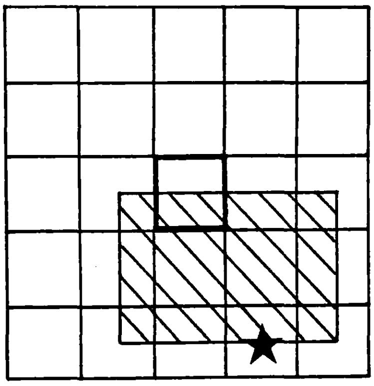
There are very few studies concerned with saccadic eye movements involving a stimulus more complex than a single point, but some findings are suggestive of the mechanism CYCLOPS uses. The balancing between amounts of stimulation to the left and right is suggested by Ingle (1968) for the frog. These animals were presented with two moving targets either side of the midline. In this situation, the frog snaps at an average position between the two. Similarly, CYCLOPS would fixate between two such evenly balanced stimuli.

Robinson (1971) has demonstrated that this may be due to mutually antagonistic patterns of behaviour being activated together. Cells in the frontal eye fields of macaque monkeys were stimulated which activated cells in the superior colliculus by means of one-to-one connections. If two cells were stimulated, one producing a saccade to the left and the other a saccade to the right, stimulation of both simultaneously produced a saccade which was the average of the two.

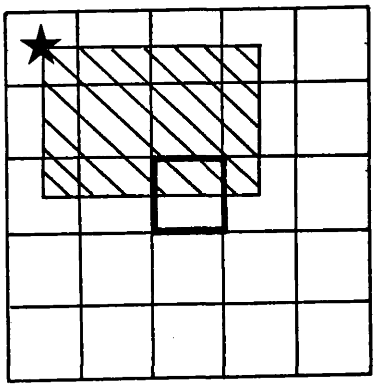
The influence of the stimulus configuration in determining the location of a fixation has been shown by



1. The fovea is fixating the bottom, left hand corner of the figure. (Heavy outline). Region ★ is selected as the target.



2. The eye movement is executed and the target fixated. Region ★ is the new fixation target.



3. Following the second eye movement a new region is fixated. Region ★ would be fixated next.

Figure 23. A series of eye movements.

$$\begin{array}{ccccc}
0 & 0 & 1 & \textcircled{1} & 1 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & * & 1 & 1 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{array}$$

1. Pattern of activity in peripheral fields during first fixation (see figure 23). * is the fovea, ○ is the target region.

distance

$$\begin{array}{ll|ccccc|cc}
\text{UP} & 24 & 0 & 0 & 1 & 1 & 1 & 3 & \\
 & 12 & 0 & 0 & 1 & 0 & 0 & 1 & 4 \\
 & & 0 & 0 & * & 1 & 1 & & \\
\text{DOWN} & 12 & 0 & 0 & 0 & 0 & 0 & 0 & \\
 & 24 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}$$

2. UP/DOWN.

   There are more regions active in the UP direction than DOWN. Of these, more are active at a distance of 24 units than 12 units. The target region will be 24 units UP from the fovea.

$$\begin{array}{l|cc|c|cc|}
 & \text{LEFT} & & & \text{RIGHT} & \\
\text{distance} & 24 & 12 & & 12 & 24 \\
 & 0 & 0 & 1 & 1 & 1 \\
 & 0 & 0 & 1 & 0 & 0 \\
 & 0 & 0 & * & 1 & 1 \\
 & 0 & 0 & 0 & 0 & 0 \\
 & 0 & 0 & 0 & 0 & 0 \\
 & 0 & 0 & & 2 & 2 \\
 & & 0 & & 4 &
\end{array}$$

3. LEFT/RIGHT

   There are more regions active in the RIGHT direction than LEFT. Equal numbers are active at distances of 12 and 24 units RIGHT of the fovea, so the smaller distance is arbitrarily chosen. The target region will be 12 units RIGHT of the fovea.

Figure 24. The selection of a target region to fixate.

```
0 0 1 ① 1
0 0 1 0 0
0 0 * 1 1
0 0 0 0 0
0 0 0 0 0
```

1. The fovea is fixating the bottom left-hand corner of the figure. ○ indicates the region selected as the target.

```
0 0 0 0 0
0 0 0 0 0
0 1 * 1 1
0 1 0 0 1
0 Ø 1 ① 1
```

2. The altered pattern of peripheral activity following the fixation of the target. ○ indicates the next target region, Ø indicates the region previously fixated which is now set to zero.

```
① Ø 1 1 0
1 0 0 1 0
1 1 * 1 0
0 0 0 0 0
0 0 0 0 0
```

3. The next pattern of peripheral activity following the second eye movement.

Figure 25. Changing patterns of peripheral activity with a series of eye movements.

Coren and Hoenig (1972). Subjects were required to fixate a central red stimulus and to shift their gaze when a red target spot appeared to the left or right at a distance of 10 degrees. Extraneous black spots were placed in a line at 1 degree intervals between the centre and target, or beyond the target. These extra stimuli influenced the location of the fixation, suggesting it was the 'centre of gravity' of the row of spots which was fixated. Spots placed beyond the target caused the fixation to overshoot, and the more spots there were, the greater the effect. The mechanism of CYCLOPS which determines the distance of a fixation from the current foveal position resembles this as it is also influenced by the amount of stimulation.

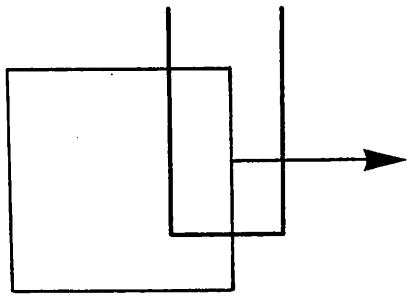
b. The foveal centering reflex.

The second oculomotor reflex operates after an eye movement, when a target has been fixated. An earlier version of CYCLOPS showed a defect caused by an inability to locate the fovea in the same position each time a region of a pattern was re-fixated. This meant that features could not be recognized because they might be located off the fovea. A series of these mis-placements would also send a sequence of fixations 'off the rails' and seriously interfered with the reproduction of scanpaths.

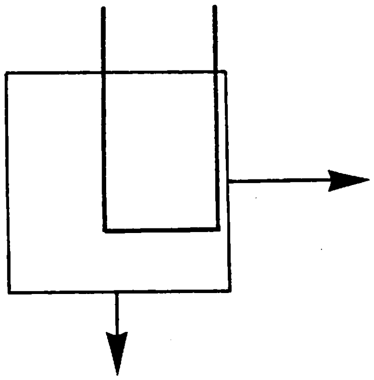
To overcome these problems, a reflex mechanism was constructed which centres the pattern on the fovea, and compensates for horizontal or vertical deviations of a few units.

The aim of the reflex is to bring all vertical and horizontal contours to the centre of the fovea, but the detection of such contours is carried out by a routine which operates faster than simple cortical processing. Within the ganglion cell array a count is made for each row and column of the number of cells which are on. An approximation is now used to judge the likelihood that there might be a contour which can be detected within each row or column. If the row or column total of active cells is less than 4, it is assumed that there is not enough contour for the simple cortical cells to detect and that row or colum is disregarded.

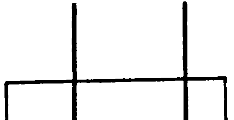
The number of the row containing the largest total of active cells (equal to or greater than 4) is noted. If more than one row has the same total, the average row number is computed. The difference between this row number and the central row number (6 is used) is obtained, and this final value indicates how much the retina must be moved up or down to centre the input. This operation is repeated for the columns of ganglion cells, and the difference value obtained which indicates the extent of a move to the left or right. This process essentially uses negative feedback to position the retina.



1. A corner is only partially seen on the fovea. If centering was not carried out, this figure would not be identified as a tongue. A horizontal adjustment is needed.



2. The first centering brings extra contours onto the fovea. Further horizontal and vertical adjustments are needed.



3. The final centering positions the complete figure on the fovea.

Figure 26. Centering the fovea

											row	total
	0	0	0	0	0	0	1	1	0	0	1	2
	0	0	0	0	0	0	1	1	0	0	2	2
	0	0	0	0	0	0	1	1	0	0	3	2
	0	0	0	0	0	0	1	1	0	0	4	2
	0	0	0	0	0	0	1	1	0	0	5	2
	0	0	0	0	0	0	1	1	0	0	6	2
	0	0	0	0	0	0	0	1	1	1	7	3
	0	0	0	0	0	0	0	0	1	1	8	2
	0	0	0	0	0	0	0	0	0	0	9	0
	0	0	0	0	0	0	0	0	0	0	10	0
column	1	2	3	4	5	6	7	8	9	10		
total	0	0	0	0	0	0	6	7	2	2		
								*				

Ganglion cell activity produced by a corner not centered on the fovea.

No vertical adjustment is needed because no row total is equal to 4 or more.

Horizontal adjustment is needed to center the vertical contour. Computation proceeds as follows -

a. Locate the column with the largest total. obtain the number of this column. In the example, column 8 has the largest total (*). If two columns share the same total, add their numbers and divide by 2.

b. In order to find what adjustment is needed to bring the contour to a central position (column 6), subtract 6 from the column number obtained above, i.e. 8-6 = +2. This means the retina must be shifted horizontally by +2 units. The outcome of this operation is shown in the next figure.

Figure 27. First stage of foveal centering.

											row	total	
	0	0	0	0	1	1	0	0	0	1	1	3	
	0	0	0	0	1	1	0	0	0	1	2	3	
	0	0	0	0	1	1	0	0	0	1	3	3	
	0	0	0	0	1	1	0	0	0	1	4	3	
	0	0	0	0	1	1	0	0	0	1	5	3	
	0	0	0	0	1	1	0	0	0	1	6	3	
	0	0	0	0	0	1	1	1	1	1	7	5	*
	0	0	0	0	0	0	1	1	1	0	8	3	
	0	0	0	0	0	0	0	0	0	0	9	0	
	0	0	0	0	0	0	0	0	0	0	10	0	
column	1	2	3	4	5	6	7	8	9	10			
total	0	0	0	0	6	7	2	2	2	7			
						*				*			

Ganglion cell activity after the first, horizontal adjustment. Extra vertical and horizontal contours have been introduced, necessitating further centering. Vertical adjustment is needed to center the highest scoring row 7 (*). The amount of adjustment is 7-6 = +1.

Horizontal adjustment now has to center two vertical contours. The highest scoring column totals are shown as *, and the two column numbers are added ie. 6 + 10 = 16. This value is divided by 2, 16/2 = 8.

The amount of adjustment is 8-6 = +2. It should be pointed out that an adjustment may have a negative value, indicating a retinal movement in the opposite direction.

The retina here must be shifted vertically by +1 unit and horizontally by +2 Units.

Figure 28. Second stage of foveal centering.

											row
	0	0	1	1	0	0	0	1	1	0	1
	0	0	1	1	0	0	0	1	1	0	2
	0	0	1	1	0	0	0	1	1	0	3
	0	0	1	1	0	0	0	1	1	0	4
	0	0	1	1	0	0	0	1	1	0	5
	0	0	0	1	1	1	1	1	0	0	6
	0	0	0	0	1	1	1	0	0	0	7
	0	0	0	0	0	0	0	0	0	0	8
	0	0	0	0	0	0	0	0	0	0	9
	0	0	0	0	0	0	0	0	0	0	10
Column	1	2	3	4	5	6	7	8	9	10	

Ganglion cell activity after the second set of adjustments. The corner which was located on the fovea initially is revealed as a tongue. Without the foveal centering reflex, this figure would not have been detected. No further centering is permitted because the maximum of 2 adjustments have been made. In this example, no further adjustment is necessary.

Figure 29. The final stage of foveal centering.

When the changes have been executed, ganglion cell processing is repeated for the altered input. The centering reflex is operated once more, and if no further adjustment is required the visual processing is allowed to continue through the various cortical levels. It may happen that the first adjustment brought new contours onto the fovea which will require another centering operation and if necessary this will be carried out. A maximum of 2 adjustments are allowed, which prevents CYCLOPS becoming stuck and continually attempting to centre the fovea.

This reflex will always bring single contours to a central position. More than one contour will be balanced around the central region. Figure 26 shows a series of adjustments produced because the initial fixation does not completely cover the figure. The first centering brings more contour onto the fovea, and a further adjustment becomes necessary. Figures 27 - 29 show in detail the processing which is carried out at each stage in Figure 26.

c. The blind move reflex.

When a series of fixations on a pattern is terminated, the blind move reflex shifts the eye away from the pattern. This move is made 'blind' because it is not aimed at any target area, but to pre-set positions. For the purposes of this reflex, the visual world is divided into quadrants.

Depending in which quadrant the fovea is situated, the blind move directs the retina into another quadrant.

Blind moves will continue to be made until a pattern is detected by the peripheral retina. When this occurs, the blind move reflex is inhibited, and the saccadic reflex takes over. Figure 30 illustrates a series of blind moves, and it can be seen that the whole of the visual world is covered after 4 moves have been executed. When an un-interrupted series of blind moves is made, each is in the same direction (clockwise in figure 30). Each time a pattern is fixated and the saccadic reflex operates, the direction of the following blind moves is reversed. CYCLOPS alternates the direction of blind moves, and this proves useful when pairs of patterns are shown side by side as the eye tends to look from one to the other without wasting time scanning empty parts of the visual world.

The blind move reflex is a simplification of the kind of search patterns which infants might be expected to use. Little is known about how infants do search for objects to fixate, but they are capable of producing wide ranging eye movements (Salapatek and Kessen, 1966, Tronick, 1972, Tronick and Clanton, 1971). A very similar search pattern was reported by Ford et al. (1959) for subjects examining a blank screen for the appearance of a spot of light. Scanning tended to follow the same direction in a

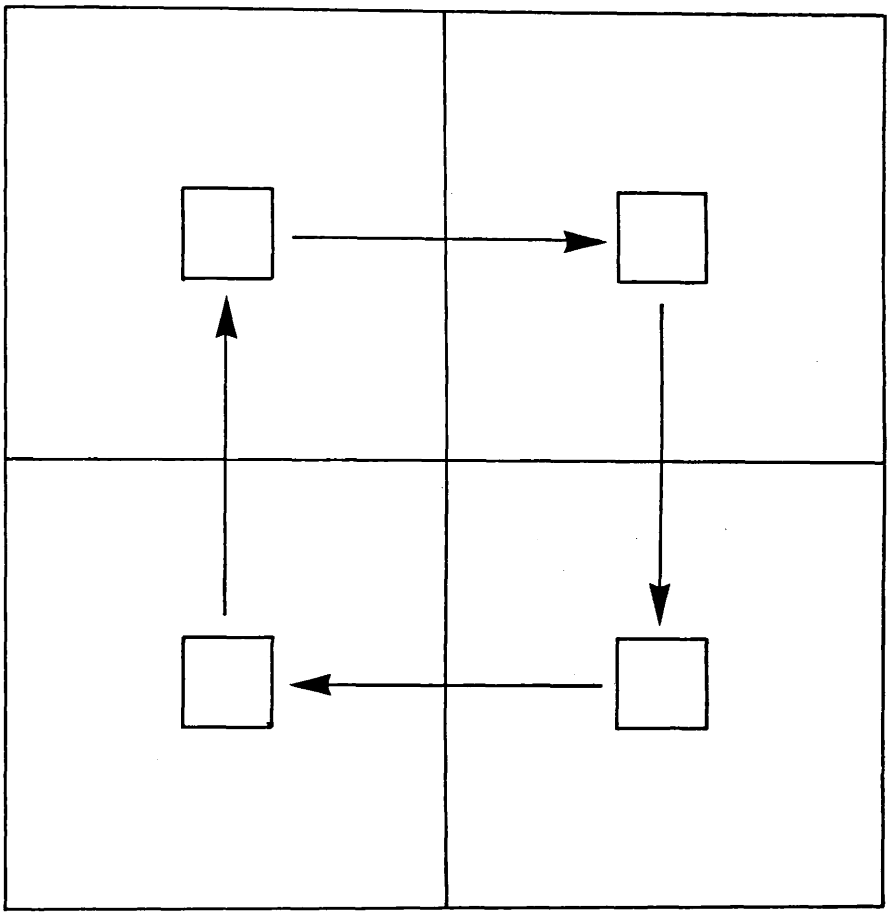


Figure 30. A series of blind moves around the visual world. The small squares indicate the successive positions of the fovea. 4 moves in clockwise direction are shown.

circular fashion, the fovea keeping to a region between the centre and edge of the screen, as in figure 30.

d. Discussion.

In the introduction to this chapter it was stated that one of the functions of computer simulation was to make explicit in a theory aspects which might not have received attention because their importance had not been appreciated. The design of the oculomotor system is an example of this, as experimentation with an earlier version of CYCLOPS revealed certain difficulties with the scanning of patterns using the saccadic reflex.

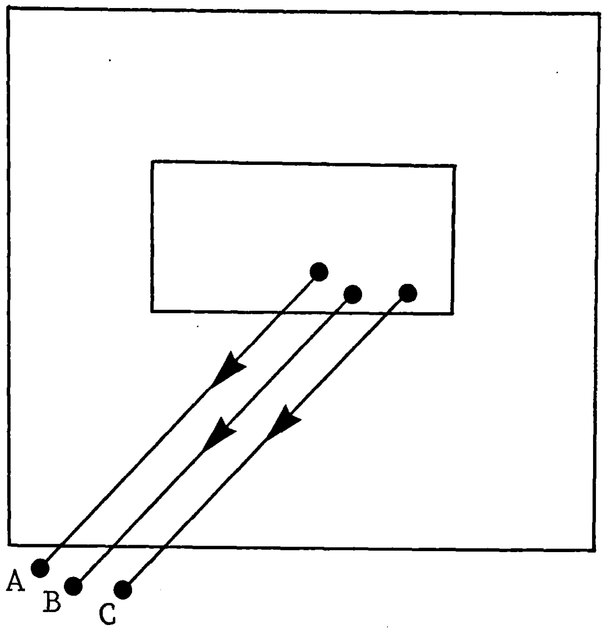
Originally, it was felt that only two reflexes were required; a saccadic reflex which would produce a series of eye movements when a pattern was fixated, and a blind move reflex to move the eye away when the series was completed. No foveal centering reflex was included, and the original saccadic reflex did not involve the peripheral inhibition of the region previously fixated. Both these components were added following initial experiments with the program.

Although the original saccadic reflex did produce a series of fixations on a pattern, it often happened that CYCLOPS was unable to re-fixate exactly the same regions when the pattern was seen again at a later stage. In some cases this had no serious effect on recognition as the same features could be detected over the whole foveal surface. However, on many occasions these small variations in the location of the fovea did interfere with recognition. Figure 31 illustrates this for 3 fixations on a corner. Slight changes in the positioning of the fovea alters the pattern of stimulation on the fovea, with the result that in A the corner is detected, but in B and C only parts are seen.

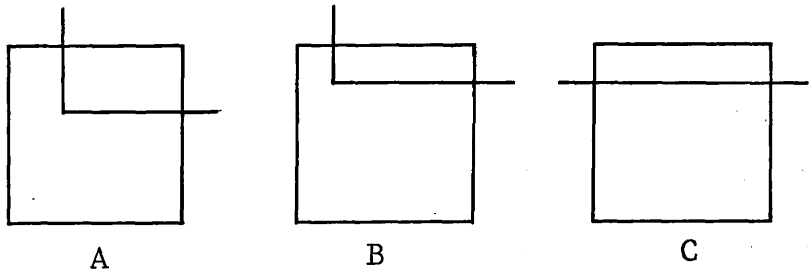
This prevented patterns being recognized, and also hampered the reproduction of the original scanpath which should be followed if recognition was to be achieved. A number of small errors in positioning the fovea would add up to a large alteration, and eventually the pattern of peripheral stimulation would be altered so that different target regions would be computed for the next fixation.

The foveal centering reflex was designed to overcome the damaging effect of these slight variations of foveal position. As figure 26 shows, moving the fovea so that contours are brought to a central position compensates for small positional variations. CYCLOPS is able to locate its fovea on the same parts of a pattern no matter where in the visual world the pattern may be situated.

Following the design of the centering reflex, an examination of the eye movement literature revealed several reports of similar 'corrective saccades' which



Fixations cluster about the corner, but each is in a different position without foveal centering.



FFL 1 1 1 0 1 0 0 1 0 0 1 0 0 1 0 0 0 0

Each fixation results in a different foveal feature list because of slight positional differences.

Figure 31, Fixations without foveal centering.

are produced by human subjects (Clark, 1936, Ford et al., 1959, Yarbus, 1967, Fuchs, 1971). It would seem these also occur to compensate for inaccuracies in the saccadic system. An eye movement locates the fovea roughly where it is intended to go, and a corrective movement performs the final adjustment, bringing the stimulus to the sensitive central region of the fovea.

A further alteration to the original saccadic reflex became necessary when it was found that many saccades were made between only 2 regions of a pattern, the eye alternating from one to the other, and failing to explore the remainder of the pattern fully. The saccadic reflex selects as a target for fixation the region which has the strongest 'pull'. It would often happen that this would be the region previously fixated, and once CYCLOPS had entered into this alternation of fixations, it was unable to stop.

The simplest means of preventing such behaviour and encouraging better exploration was to temporarily inhibit an eye movement which would return the fovea to the region previously fixated. This was achieved by setting the appropriate peripheral region to 0, so that even if it was selected as the target region, another would have to be chosen. This addition successfully prevented the alternating fixations and produced more wide ranging scanning. It is interesting that Didday and Arbib (1973) make a similar provision in their model by deleting a region from the superior colliculus each time it is fixated. However, once deleted, a region in their model is not re-instated, and will not be re-fixated. CYCLOPS only inhibits the one region that was previously fixated, and it may be looked at again at a later stage.

When the model was first constructed, neither of these difficulties was expected, but observation of the model 'in action' by means of computer simulation quickly revealed the drawbacks. Because these defects seriously interfered with the expected scanning behaviour,the other theories of eye movements and pattern recognition (Hebb, Noton and Stark, Didday and Arbib) can be criticized for not including a sufficient account of the behaviour they intended to explain. CYCLOPS is an advance over these theories as it shows that more consideration of the scanning mechanisms must be included if the theory is to be useful.

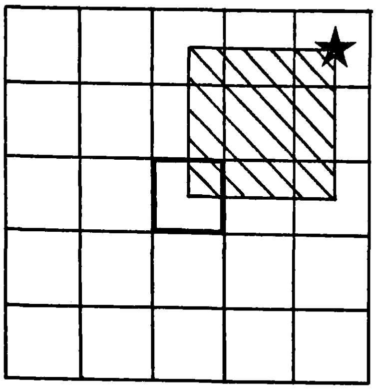
CHAPTER 5.

THE COMPUTER MODEL: MEMORY AND LEARNING.

1. Perceptual analyzers

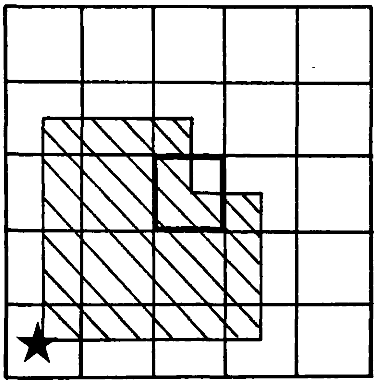
The basic perceptual unit or 'analyzer' which was described in Chapter 2 has two components, each derived from separate parts of CYCLOPS' visual system. The features detected on the fovea by the successive levels of cortical processing are combined in a coded foveal feature list (FFL). This list forms one part of an analyzer, the other being supplied by peripheral vision. During a fixation on a pattern, the saccadic reflex selects one peripheral region which contains contour as a target region. This peripheral target region may be located in any one of 24 peripheral regions, and so is identified by a number from 1 to 24 (see figure 22a). This peripheral target region (PTR) forms the second part of an analyzer.

It is important to note that an analyzer has these two distinct components. This means that analyzers may differ in their feature lists, peripheral target regions, or both. Figure 32 shows fixations on two different patterns. In each case the same set of features is detected on the fovea, resulting in the same foveal feature list, but different analyzers are created because the saccadic reflex computes different peripheral target regions



1. The fovea is fixating the lower, left-hand corner, and the peripheral target region is indicated by ★ The analyzer appropriate to this fixation has these components -

FFL	PTR
1 1 1 0 1 0	20



2. The pattern is different, but CYCLOPS detects the same set of features. Despite this, a different target region is computed and a new analyzer is appropriate -

FFL	PTR
1 1 1 0 1 0	5

Fig. 32. Perceptual analyzers.

for each figure.

2. The structure of memory.

Analyzers are stored in a large array, each row being assigned to a different analyzer (see figure 33). Analyzers are identified by the number of the row in which they are stored, and this may range from 1 to N. The first two entries in a row of the array record the analyzer components. The first is the list of foveal features; the position of a number in this list indicating the type of feature, and the value of a number specifying the frequency of such features detected on the fovea. The second entry in the row records the peripheral target region computed by the saccadic reflex for each analyzer.

The third entry in the row is the prediction list belonging to the analyzer. This is a list of numbers, each of which refers to a row of the array, and thus to the combination of foveal features and peripheral target region (ie. the analyzer) stored in that row. The prediction list records those analyzers, one of which CYCLOPS expects to match with the input obtained during the next fixation. The length of the prediction list may vary from 0 to N, reflecting the choice of analyzers from which CYCLOPS may achieve a match.

ANALYZER			PREDICTION LIST						
Number	FFL	PTR	1	2	3	4	5	...	N
1	1 1 0 1 0 2	10	2	0	0	0	0		0
2	0 1 0 0 0 0	16	3	0	0	0	0		0
3	1 1 1 0 1 0	7	4	0	0	0	0		0
4	1 1 0 1 2 0	19	5	7	0	0	0		0
5	1 1 0 1 0 1	4	6	0	0	0	0		0
6	1 1 1 0 1 0	15	7	0	0	0	0		0
7	0 1 0 0 0 0	7	8	1	3	0	0		0
8	1 2 1 0 0 1	1	0	0	0	0	0		0
9	0 0 0 0 0 0	0	0	0	0	0	0		0
10	0 0 0 0 0 0	0	0	0	0	0	0		0
•									
•									
•									
N	0 0 0 0 0 0	0	0	0	0	0	0		0

FFL = Foveal feature list

PTR = Peripheral target region

Each analyzer is assigned a separate row in the array. 8 analyzers are shown, the remaining rows being blank and available for new entries. Some analyzers share the same FFL (eg. 2 and 7) but differ in the PTR. The numbers in the prediction lists refer to rows of the array, and thus to the FFL and PTR stored in those rows (ie. the analyzer). Prediction lists record the analyzers, one of which CYCLOPS expects to identify during the next fixation.

Figure 33. The structure of memory.

3. Pattern learning during scanning.

When a pattern is detected by the peripheral retina, the saccadic reflex computes which peripheral region is to be the target, and a movement is executed to bring that region onto the fovea. CYCLOPS examines each row of the array to find an analyzer which matches the input obtained during the fixation. The matching procedure is carried out in two stages (but see footnote 1). Firstly, for each row of the array, the list of features detected on the fovea is compared with the list stored in the row. If there is any discrepancy between the two, that analyzer is rejected and the next row examined.

If the two foveal feature lists are the same, the number of the peripheral target region stored in the same row is noted. The current state of the peripheral region identified by this number is examined. If the state of this peripheral region is zero, the analyzer is rejected, and the next row examined. If the state of this region is 1, the analyzer

Footnote 1. Searching for a matching analyzer through the array in figure 33 would be time consuming as an exhaustive search is required. In the program, the array is split into 2 parts to speed the process. FFL's are recorded in a separate array, and an exhaustive search is made to match the input FFL. This is not a lengthy process as the number of FFL's is not great. Once located, the search can then be directed to only those analyzers of which the FFL is a component. This arrangement is structurally identical with that of figure 33, but computationally much more efficient.

stored in that row of the array is selected and no further rows of the array are examined.

A distinction should be drawn between these two stages of the analyzer matching procedure. The comparison between the stored and currently obtained lists of foveal features is quite straightforward and requires an exact agreement if a match is to be achieved. The examination of the peripheral target region does not involve such a comparison, and is simply an examination to determine whether a contour is indicated within that region (state = 1). The analyzer matching procedure requires that only one specific peripheral retinal region currently indicates contour, and the states of the remaining regions are irrelevant.

It should also be stressed that it is not the saccadic reflex which determines the peripheral region that is examined, but the peripheral target region stored in the row of the array. There is no requirement that the peripheral target region which the saccadic reflex would compute during the fixation has to be the same as that belonging to the analyzer, and in fact the saccadic reflex has not performed any computation when the analyzer matching process is carried out.

If an anlyzer which matches the input is found, the numbers in the prediction list of the row in which the analyzer is stored are noted by CYCLOPS for the next fixation. An eye movement is then executed to bring the peripheral target region specified by the analyzer onto the fovea.

During the subsequent fixation, CYCLOPS first attempts to find an analyzer which matches the new input from those analyzers referred to by the numbers in the prediction list. Each is compared with the input until one which matches is found. CYCLOPS then repeats the procedure outlined above; the numbers in the new prediction list of the row containing the matching analyzer are noted, and the eye movement is executed which brings the peripheral target region stored in that row onto the fovea.

If none of the analyzers stored in the rows referred to by the prediction list match the input, CYCLOPS makes a serial search through all the rows to find any analyzer which matches. When one is found, the number of the row in which it is stored is entered into the prediction list of the row belonging to the analyzer which matched the previous input,and a new prediction is created. The number is entered in the first space of the prediction list (going from left to right) which does not already contain an entry. In this manner, CYCLOPS is able to learn new patterns, so that when the patterns are re-fixated, the prediction lists will contain the numbers of analyzers that match the input.

At any stage of this process it may occur that no analyzer stored in any row matches the input during a fixation. In this situation a new one is created, and the first available row in the array is allocated to the new analyzer. The list of features detected on the fovea is copied into the first part of the row, and the number of the peripheral target region computed by the saccadic reflex is entered into the second part. The exception to this rule is when the foveal feature list is blank because the fovea is situated on a part of the visual world which lacks contour. In this case, no analyzer is created. Although the features which are processed by the cortex are fixed or 'innate', their combinations and associated peripheral target regions are acquired. The ability to generate analyzers has been found to be a considerable advantage for pattern recognition systems (Uhr and Vossler, 1963, Uhr, 1973), and CYCLOPS generates new ones when necessary.

When a new analyzer has been created, the number of the row in which it is stored is not entered into the prediction list of the row containing the analyzer which matched the previous input. This means that pattern learning is a two-stage process with CYCLOPS, analyzers being acquired first and prediction lists later. Hebb (1949) also proposed a two-stage model of learning; early learning consisted of the acquisition of cell assemblies and lower order phase sequences, while later (adult) learning involved linking these primitive units into more complex sequences.

4. Pattern recognition

CYCLOPS recognizes patterns by making a series of fixations for which one of the predicted analyzers matches the input obtained during the fixation. Recognition is said to occur if the input is correctly predicted for each of a series of fixations, with the exception of the first one. In this initial case, a search must be made through the memory array until an analyzer is found which matches the input. The matching procedure outlined in section 3 is followed; the stored and current input lists of foveal features are compared, and the analyzer determined peripheral target region on the retina is examined to see if it is in state 1. Once a matching analyzer has been found, the numbers in the prediction list contained in the same row indicate which rows are to be examined first during the next fixation. This matching procedure is the same, and the rows specified by the numbers in the prediction list are examined in turn. The first analyzer to match the input is selected, and further examination of the rows specified by the prediction list is stopped.

Making predictions about which analyzers will match the input has three important roles. Firstly, a prediction will often resolve any ambiguity about which analyzer matches the input. If a serial search was made through memory each time, the first matching analyzer would always be selected. The prediction list overrules this choice by specifying a list of preferences which must be checked first. It could also happen that several different analyzers might potentially match the current input. Each would have a list of foveal features which matched the current feature list, and the peripheral target regions, though different for each analyzer, would all be in state 1 in the current peripheral retinal input. The prediction list resolves this potential ambiguity by specifying which analyzers are to be compared with the input, and stopping further examination when the first matching one is found.

Secondly, recognition is speeded up because exhaustive searches through memory are not always necessary at each fixation. The numbers in the prediction list direct the search to specific rows in the memory array. Failure to match any predicted analyzer will, of course, require an extensive search to be made. Finally, the outcome of the matching process provides a means by which the degree of familiarity of the pattern which is being scanned may be assessed, a point which is discussed in the next chapter.

When a matching analyzer has been found, an eye movement is made to fixate its peripheral target region. This is achieved by biasing the operation of the saccadic reflex. All active regions in the peripheral retina except for the target region are inhibited and set to Zero. When the saccadic reflex computes the target region for the next fixation, the analyzer-determined target is the only active region, and so is automatically selected (but see footnote 2).

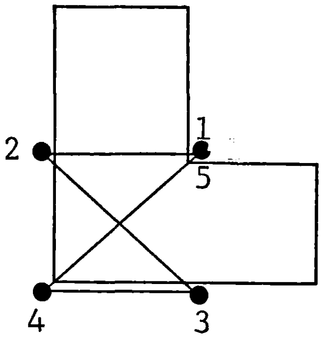
The biasing of the saccadic reflex means that the target region which normally would have been computed by the reflex is overruled, and the one determined by the analyzer takes its place. In many cases these two targets are likely to be the same region, but the overruling occurs enough times to have a significant influence on CYCLOP'S scanning behaviour. Thus matching an analyzer with the input means that the subsequent eye movement is already determined. This is the reason that the peripheral target region specified by the analyzer must be in state 1. If it was in state 0, the saccadic reflex could not produce

Footnote 2. Although the biasing of the saccadic reflex was achieved in this manner in an earlier version of the program, the process is speeded up in the current version by by-passing the saccadic reflex computation and directly fixating the analyzer-specified target region. The outcome of this modification is identical but achieved faster.

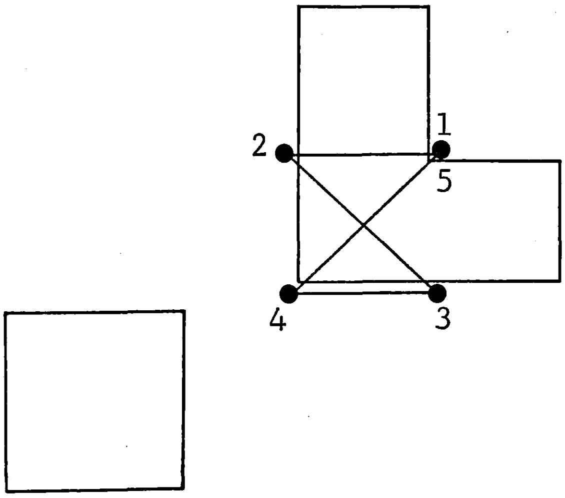
an eye movement to fixate the region as such movements are not permitted.

This domination of the saccadic reflex is an important part of the recognition process as it will result in habitual scanpaths being used to fixate patterns. Recognition consists of making a correct series of predictions about the input received with each fixation, and making fixations in the same order each time. These two processes support each other; predictions will not match the input unless fixations do occur in the same order, and predictions ensure that the correct analyzer (and hence the correct target region) is specified.

These points are illustrated in the next three figures. Figure 34a shows the scanpath which resulted when CYCLOPS was shown an L-shaped figure, (shown in outline), the fovea initially being positioned at point 1. Figure 34B shows the scanpath which appears when the L-shaped figure is seen again, coupled with a square. It will be seen that exactly the same scanpath is followed as appeared during the first presentation. Figure 35 reveals the scanpath which appears for the pair of figures with a version of CYCLOPS that has had no prior experience with the L-shape. This scanpath is completely different from the previous one, and shows what the saccadic reflex would normally produce. In figure 34b, the analyzers and

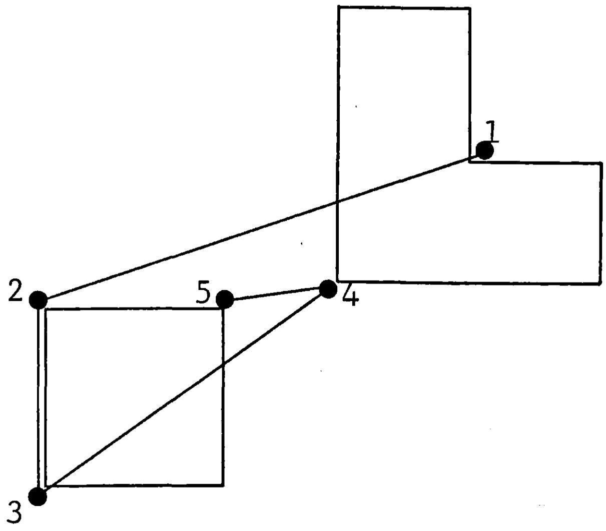


a. CYCLOPS produces this scanpath when shown the L-shape. The fovea is positioned at point 1, 4 eye movements follow; Each point indicates the central region of the fovea.



6. After seeing the L-shape, CYCLOPS is shown the same figure with a square. The original scanpath appears again.

Fig. 34. The influence of experience on scanpaths.



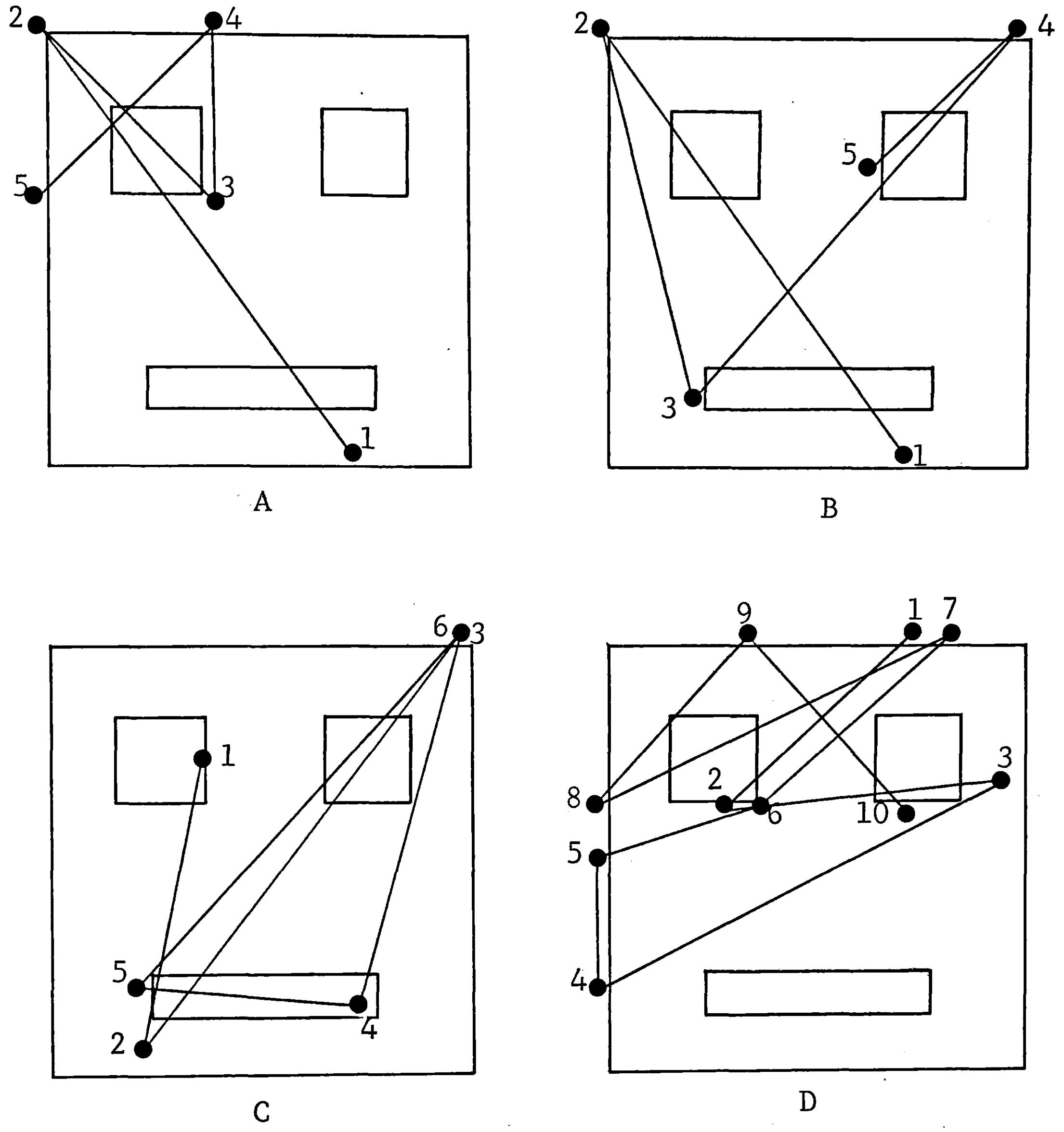
This version of CYCLOPS has not seen the L-shape before. The scanpath is very different from the one in figure 34b because the saccadic reflex is not biased.

Fig. 35. The influence of experience on scanpaths.

predictions acquired from looking at the L-shape overrule the saccadic reflex, which would otherwise draw the eye towards the square.

Figure 36 illustrates a pattern which was shown to 4 different versions of CYCLOPS, each of which had a different history of visual experiences. Figure 36A shows the scanpath which appeared when nothing else had been seen previously, and so is uncontaminated by the effects of experience. B shows the scanpath for a version of CYCLOPS which had seen a number of different patterns, and although the first two fixations are the same as in A, the remainder are very different. CYCLOPS had established a set of analyzers, some of which were appropriate for this pattern, and they overruled the scanpath which the saccadic reflex alone would have produced. Figures 36C and D show two longer scanpaths for versions which had also seen a number of different patterns. These are longer than the scanpaths in A and B because the patterns were moderately discrepant, and the sequences of fixations were terminated later by blind moves (discussed in the next chapter).

Although some scanpath variation is due to the initial fixations being made at different positions, the influence of experience is apparent. For example, in C fixation 3 is on the same corner as fixation 4 of B, but the location



This figure was shown to 4 versions of CYCLOPS, each with a different visual experience. A shows the scanpath when nothing has been seen previously; B, C and D have each seen some patterns before. C and D are longer because the pattern was moderately discrepant. Variations in scanpaths are due to differing positions of fixation 1, and to different analyzers being matched with the input.

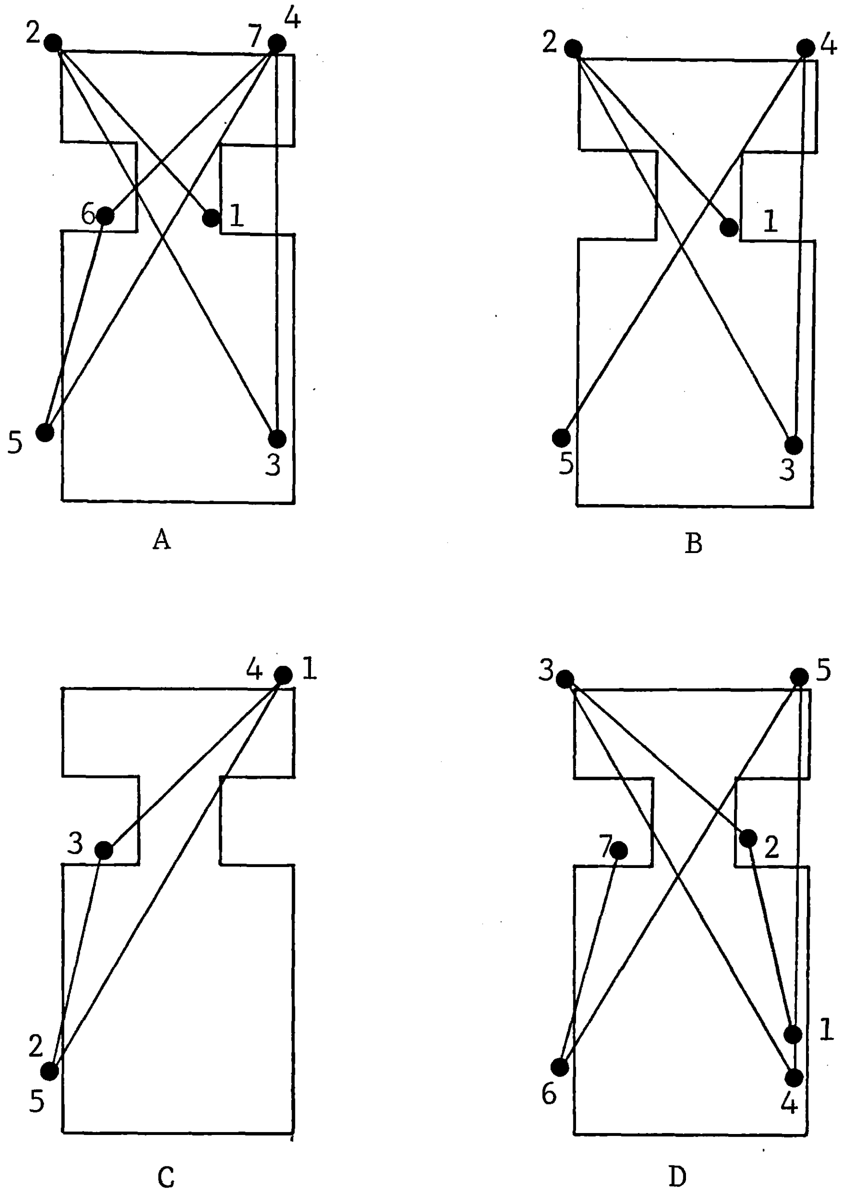
Fig. 36. The effects of varied experience on scanpaths.

of the subsequent fixations differs. Didday and Arbib (1973) also reported individual styles of scanning with their computer model, but this required the interference of the operator on the program. CYCLOPS does not require operator assistance, and introduces its own variation.

5. <u>The recurrence of scanpaths during recognition.</u>

The correct prediction of analyzers during a sequence of fixations on a pattern necessarily means that the original sequence of eye movements will be repeated. This is so because each analyzer specifies a peripheral target region which will bias the saccadic reflex, and automatically produce an eye movement to fixate that region. As a result, the scanpath which appeared while CYCLOPS was learning a pattern tends to recur when the pattern is seen again.

Figure 37 shows an example of this with 4 successive presentations of a pattern. In A, the pattern is seen for the first time, and the scanpath is the one which appeared while it was being learned and new analyzers were created. Figure 37B shows the scanpath which was followed during a later look at the pattern. It will be seen that most of the original sequence is reproduced, each fixation being on the same regions and appearing in the same order. The total number of fixations (ie. the length of the look) differs in these examples according to



Scanpath A was produced when CYCLOPS saw this pattern for the first time. B is a later presentation, and most of the original is reproduced. C and D were produced during later looks, and again most fixations belong to the original scanpath.

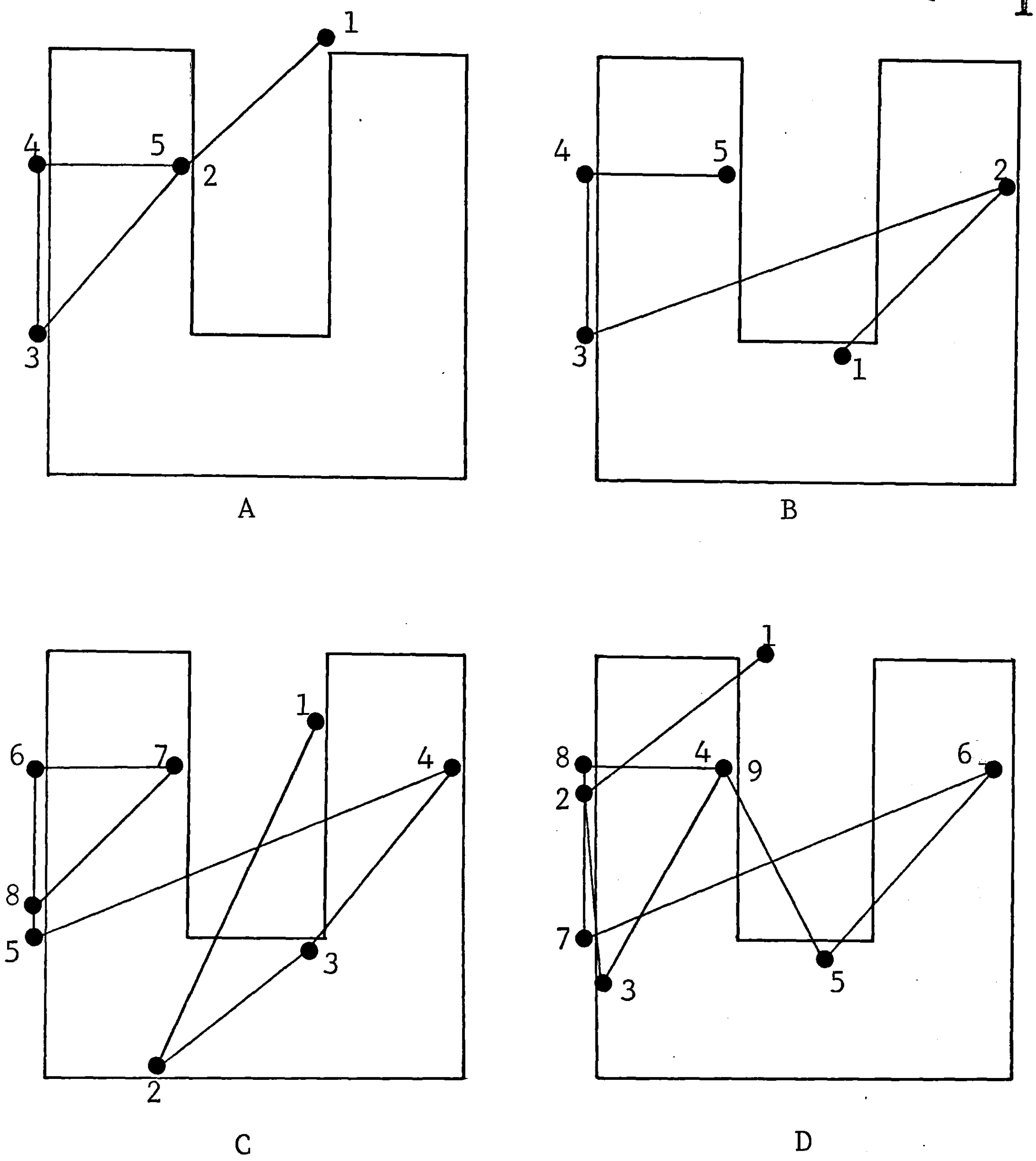
Fig. 37. The recurrence of scanpaths during recognition: 1.

the amount of discrepancy which exists between the pattern that is scanned and what is stored in memory. The operation of this mechanism will be discussed in the following chapter. Two later looks shown in figures 37C and D indicate the further recurrence of the original scanpath.

Figures 38 and 39 illustrate the recurrence of scanpaths for two other patterns, but here there is more variability. This is mainly due to the initial fixation being positioned on part of the pattern which had not previously been explored, eg. Figures 38B and C. After some initial fixations, part of the initial scanpath recurs.

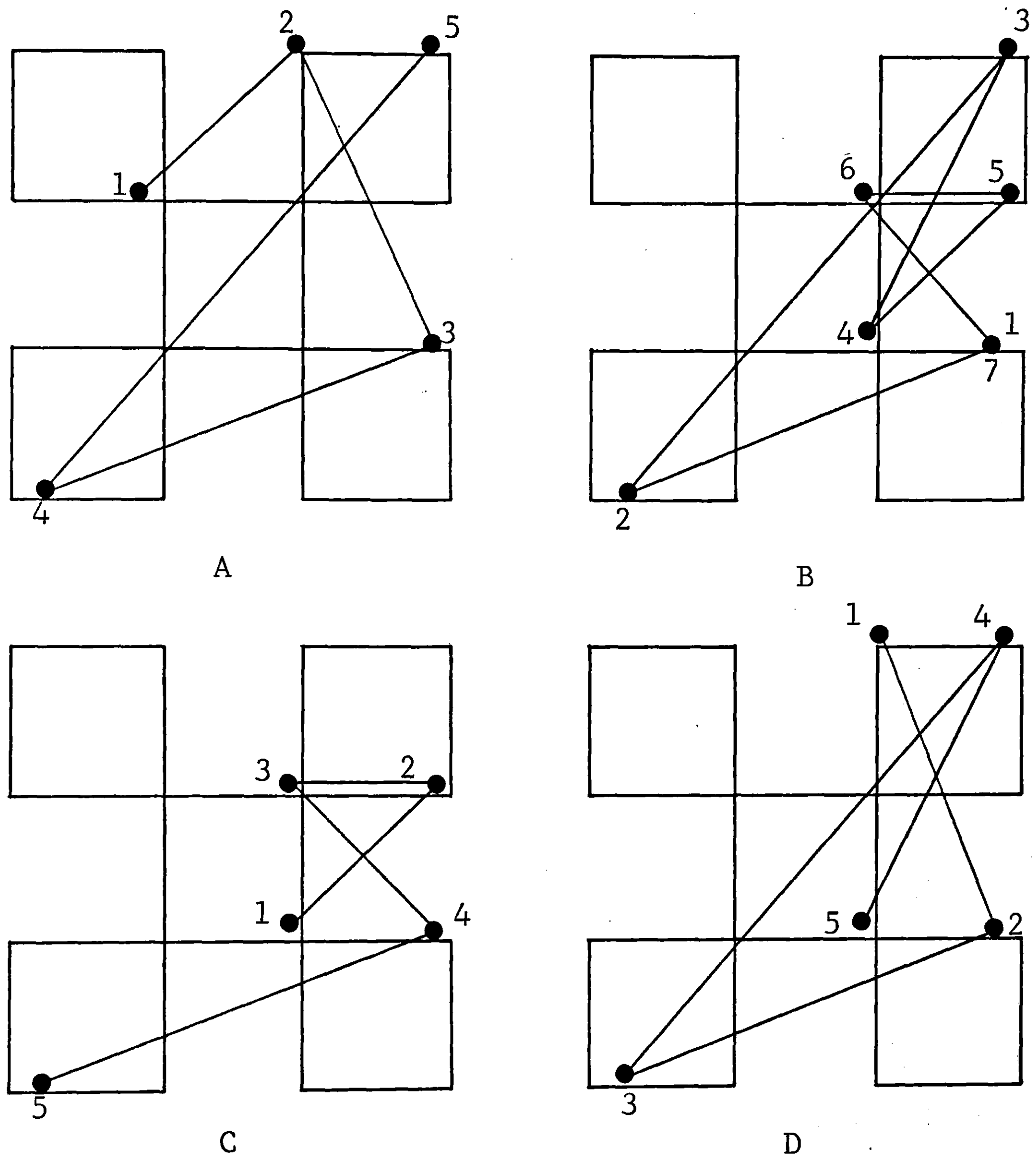
Figure 39 is interesting because it shows two types of scanpath which re-appear for the same pattern. Illustrations A and D have almost identical series of wide ranging eye movements, but B and C show fewer of these. Instead, B and C share the same series of small eye movements between fixations on the right-hand portion of the pattern.

One interesting finding is that a scanpath which appears for one pattern may sometimes re-appear for another pattern, indicating the generalization of recognition. Figure 40 gives one example of this for several patterns which have a vertical oblong shape in common, though none



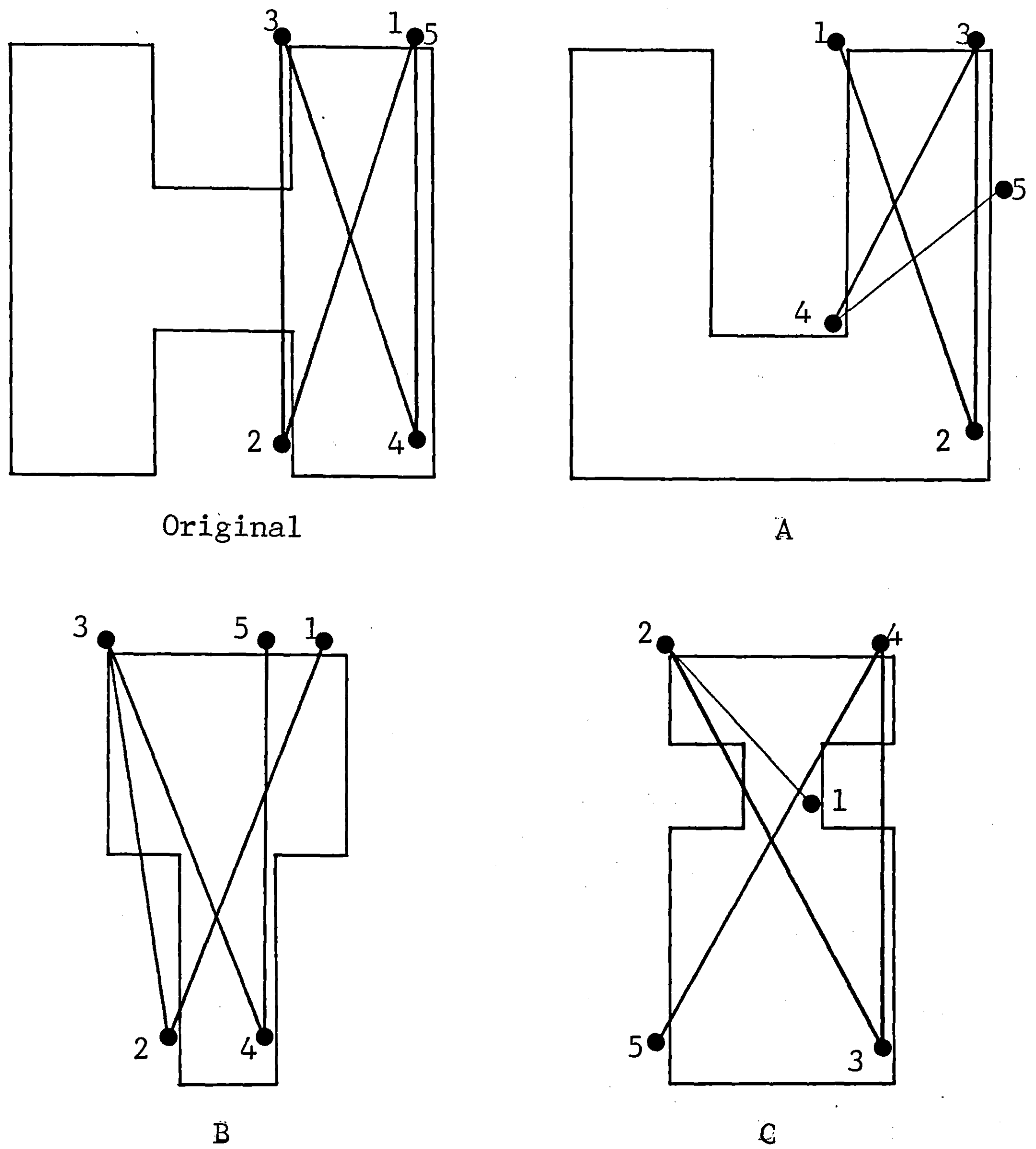
This pattern was shown to CYCLOPS several times. Scanpath A was followed while it was being learned, B - D were followed when it was recognized. The amount of repetition varies, but certain fixations and their order of appearence are common to each look.

Fig. 38. The recurrence of scanpaths during recognition: 2.



This pattern would seem to have resulted in 2 types of scanpath. The looks shown in A and D are wide ranging and the scanpaths have more in common than the others. Looks B and C show fixations concentrating at the right of the pattern. Despite this, all four scanpaths have points in common.

Fig. 39. The recurrence of scanpaths during recognition: 3.



Original

A

B

C

3 separate versions of CYCLOPS were shown the original pattern, and then one which was different. In each case, part of the original scanpath appeared for the different pattern. Fixations were made in the order indicated; parts of the original scanpath are emphasized. Each version, A. B and C, show some alterations due to variations in pattern sizes which cause the fovea to be centered in different positions.

Figure 40. The recurrence of scanpaths with different patterns.

is identical. Three versions of CYCLOPS were each shown the original, and then one of three alternative patterns. Fixations were made on similar parts of each pattern, and the original scanpath was reproduced. Some variation occurs in the actual location of fixations because differences in the patterns affected the foveal centering reflex. Despite this, it will be seen that fixations were made in the same order, and the same analyzers were identified for each of the patterns.

One noticeable feature of the scanpaths shown in figures 38 and 39 is that while the same fixations tend to be made in the same order with each presentation, the scanpaths are not identical. Variation occurs usually because the location of the initial fixation is on a region which has not previously been fixated, either because the pattern was presented in a different position, or because CYCLOPS was exploring a new part of the visual world when the pattern was detected peripherally. Variation may also arise when the original scanpath has been reproduced completely, but CYCLOPS continues to fixate the pattern. In this case new regions which were not included in the original scanpath will be fixated. These two influences result in CYCLOPS repeating a scanpath to a greater or lesser extent. This is also characteristic of the scanning observed experimentally by Noton and Stark (1971a) and Locher and Nodine (1974). The Noton and Stark model predicts that scanpaths will be rigidly repeated, and is unable to account for such variations. Such variation, as the computer simulation reveals, is the norm for CYCLOPS' scanning behaviour.

CYCLOPS is able to reproduce scanpaths because of a relatively simple mechanism. Instead of performing the lengthy computation by the saccadic reflex to identify a peripheral target region, it is only necessary to check that the peripheral region specified by the analyzer is active. This process is important for recognition since some peripheral information is involved as well as the foveal features, and the analyzer records something of the structure of a pattern. This information is then used to produce an eye movement with the result that the original scanpath is followed. The analyzer is thus a sensori-motor device, being used by CYCLOPS to match the retinal input and then to control the subsequent eye movement.

CHAPTER 6.

THE COMPUTER MODEL: THE DISCREPANCY PRINCIPLE.

1. The discrepancy index.

The amount of looking a pattern receives depends on how similar it is to patterns which have been seen previously and the amount of discrepancy which is discovered between the pattern which is looked at and the patterns already stored in memory. A look will be short if the discrepancy is too low or too high, but it will be long if the amount of discrepancy is between these extremes. With CYCLOPS, the length of a look cannot be measured in terms of time, but instead the number of fixations which occur during a look provides a suitable measure of its length.

The assessment of the amount of discrepancy must be made while a pattern is being scanned; it would be of little use if CYCLOPS made a large number of fixations and then discovered they were not discrepant with the contents of memory when it was too late to produce only a short sequence. This difficulty is avoided by rating a sequence of fixations on an index of discrepancy, and adjusting the rating as each new fixation is made.

The discrepancy index has two ends, the lower corresponding to low discrepancy (ie. familiar), and the upper corresponding to high discrepancy (ie. novelty). The status which a sequence of fixations has reached is recorded by a pointer which may be moved up or down the index. When the pointer moves beyond either of the two ends, further scanning of the pattern is prevented, and the blind move reflex moves the eye away.

The movement of the pointer along the discrepancy index depends on the outcome of attempting to find a predicted analyzer which matches the current input. When a pattern is initially fixated, the pointer is set mid-way between the two ends of the index. With each successive fixation, if one of the predicted analyzers matches the current input (indicating that something is recognised), the pointer is moved one step towards the lower (ie. familiar) end of the index. If there is a mis-match, either because no predicted analyzer matches or because none were predicted, the pointer is moved one step towards the upper (ie. High discrepancy) end of the index.

The effect of this scheme is to alter the number of fixations which are made depending on the number of matches and mis-matches which occur. The discrepancy between a sequence of fixations and the contents of memory is defined in terms of the outcomes of attempting to predict which analyzer will match the input at each fixation. A sequence which is familiar will produce a series of matching predictions and the pointer will quickly move beyond the low-discrepancy end of the index, causing the eye to look away with a blind move. A sequence of fixations which is totally new will result in a series of mis-matches that will move the pointer beyond the high-discrepancy end, again resulting in a blind move which shifts the eye away from the pattern.

If some of the predictions match the input but some mis-match, the pointer will hover in the central region of the index, and consequently the length of the look will be greater than in either of the two previous conditions. Such a sequence of fixations would be moderately discrepant, and confining the pointer to the central region of the index delays the occurrence of a blind move and results in a longer fixation sequence.

The length of a series of fixations is also affected by the amount of separation between the ends of the discrepancy index. Unless otherwise stated, all experiments with CYCLOPS used an index with a separation of 5 spaces. The lower end was set at 0, and the upper at 6, with the pointer located at 3 (the mid-point) when a fixation sequence began. If an un-interrupted series of matching predictions was made, the pointer occupied the following successive positions; 3, 2, 1, 0, -1, at which point a blind move terminated the sequence. This sequence permitted 5 fixations to be made. If the separation was greater, for example 9 spaces, the pointer would initially be positioned at 5, and the following positions would occupied successively; 5, 4, 3, 2, 1, 0, -1. This sequence is longer, permitting 7 fixations to be made. The effects of such changes to the length of the discrepancy index will be illustrated in the next chapter.

2. Reasons for incorporating the discrepancy principle in CYCLOPS.

The discrepancy principle is a necessary component of CYCLOPS, and by implication for any developmental theory of perception involving eye movements and pattern recognition. The reasons are set out below.

a). It is essential for the model that some control exists to prevent endless scanning of a pattern. Without such a control, CYCLOPS would fixate the same pattern until the program stopped running, never looking away by means of a blind move. This is particularly likely to happen if a region is re-fixated during a look. This would result in the continual repetition of the same cycle of fixations. While there is some indication that several cycles may appear (Yarbus, 1967, Zusne & Michels, 1964), it is certain that this would not continue indefinitely. The discrepancy principle means that recognition will be achieved as economically as possible when a certain number of matching predictions have been made.

b). At the same time, it would be unsatisfactory if only a set number of fixations was allowed since all looks would be equally long. Experimental recording show great variation in the lengths of looks which stimuli receive, and flexibility in the amount of looking will increase the chances of recognition. It often happens that CYCLOPS makes initial fixations on regions which have not been looked at before and about which no predictions can be made. If the length of a series of fixations was rigidly fixed, it is unlikely that the pattern would be recognized. The first fixations would be used up on unknown regions, and as soon as a few fixations were made which did result in matching predictions, the sequence would be terminated. With the discrepancy principle, fixations would continue to be made, and a greater number of matching predictions could be achieved. A fixation sequence which appeared new at the start would be revealed as familiar as more fixations were made.

c). The principle encourages CYCLOPS to look more at patterns which are not completely familiar, hence the opportunities for learning new patterns are greater. The limit on the length of a sequence in which each fixation has a matching prediction means that CYCLOPS does not spend too much time examining what has already been learned.

d). The principle encourages CYCLOPS to build coherent memories. A long series of fixations (and hence the acquisition of new predictions) will only be made when some existing predictions match the input during the sequence. This means that new material will tend to be acquired when it has something in common with the existing contents of memory.

e). The principle, as implemented in CYCLOPS by means of the discrepancy index, results in patterns of looking which resemble infant behaviour. This point will be dealt with more fully in the next chapter.

3. The complete program.

The main parts of CYCLOPS have all been described, but before proceeding with the illustrations of CYCLOPS' behaviour it is necessary to show how these parts fit together. Figures 41 and 42 are flow diagrams which show how the program is organized. The nodes are individually numbered from 1 to 20, and included within each are the chapter and section numbers which deal with the contents of each

For each fixation, following either a blind move or a saccade, the program begins at node 1 by centering the fovea. At node 2 the list of features detected by the visual cortex on the fovea is produced (FFL). This is followed at node 3 by the processing of the peripheral retina, in which each peripheral region is set at state 1 or 0 depending on whether contour is detected within the region. At node 4, the peripheral region~~s~~ which was previously fixated ('previous PTR') is set to zero to prevent it being re-fixated. At this stage, processing of the current retinal input is completed.

An examination is made of the analyzers specified in the prediction list to find if any matches the input (node 5). If one of the predicted analyzers does match, the program passes to node 6, and the pointer is moved one step down the discrepancy index. The position of the pointer is checked at node 7. If it is within the limits of the index, the prediction list associated with the matching analyzer is noted (node 8), and an eye movement is made to fixate the peripheral target region specified by the analyzer (node 9). The program then returns to node 1 for the next fixation.

If at node 7 the pointer had gone beyond either of the ends of the discrepancy index, the sequence of fixations would be terminated. The pointer is returned to the centre

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node, eg. 99:295 refers to pages 99 and 295 the second number indicating the page containing the appropriate program code.

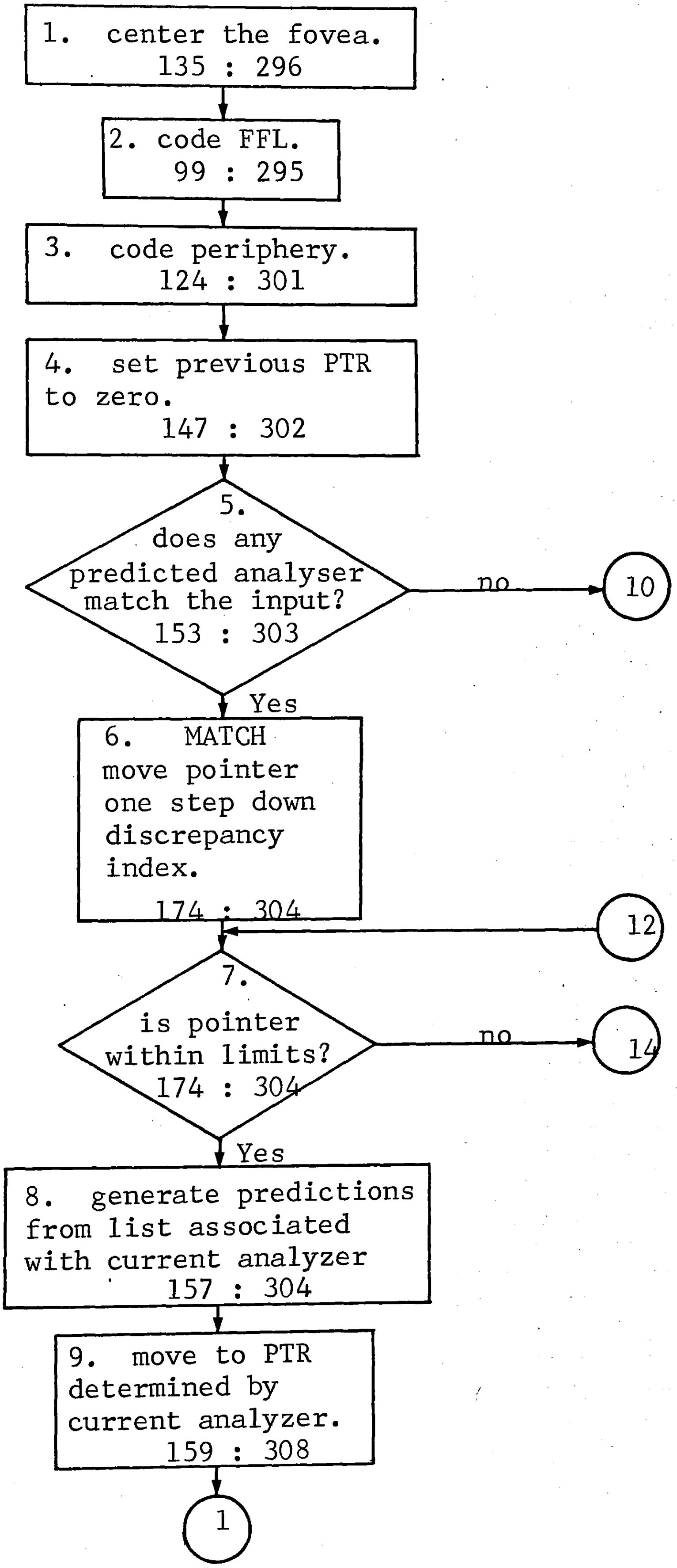


Fig. 41. CYCLOPS flow diagram, Part 1.

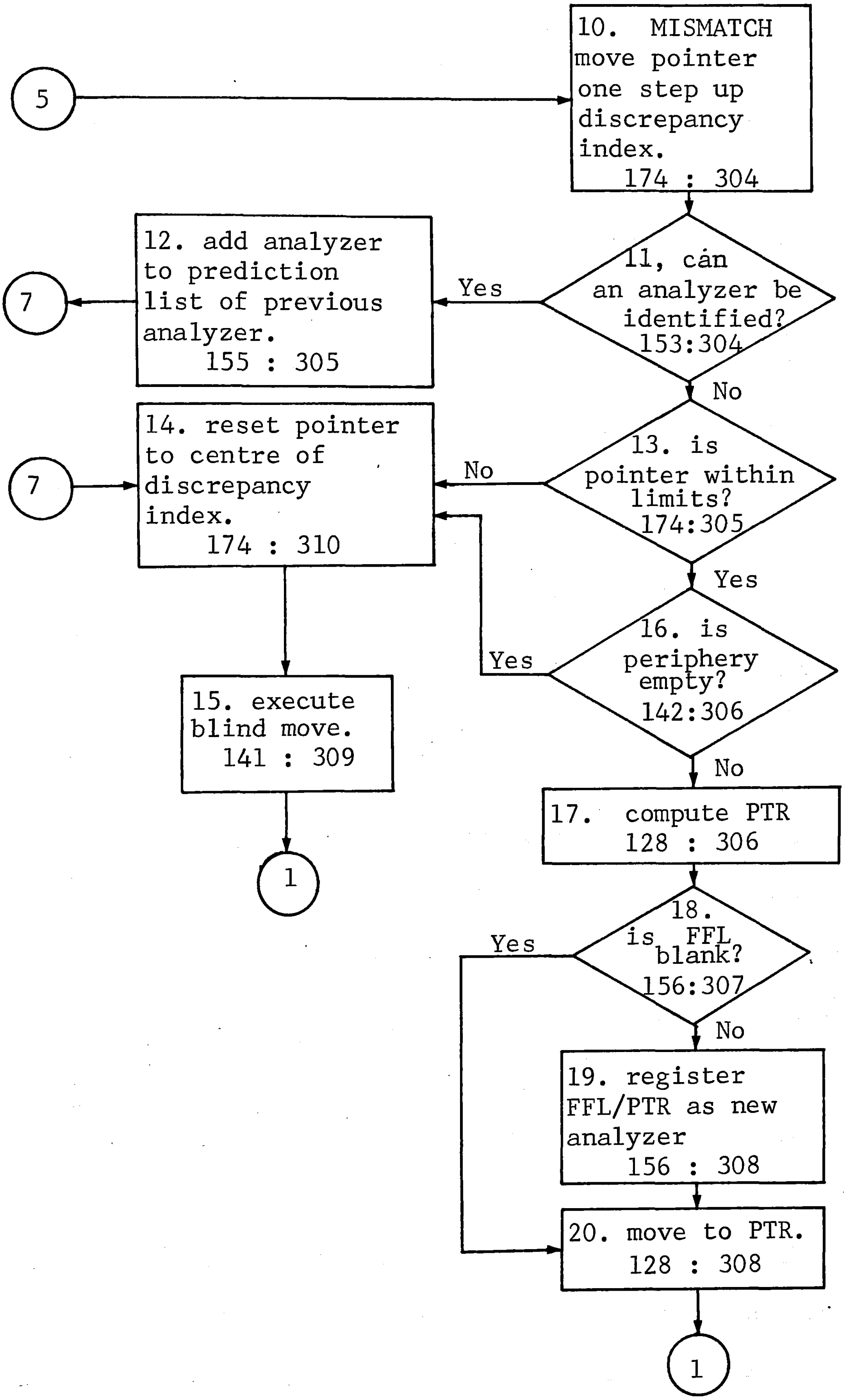


Fig. 42. CYCLOPS flow diagram, Part 2.

of the index (node 14), and a blind move is executed to move the eye away from the pattern which was scanned (node 15). The program returns to node 1 for the next fixation.

Returning to node 5, it could happen that no predicted analyzer matched the input, or there were no predictions at all. In either case there would be a mis-match between the predictions and the input, and the pointer is moved one step up the discrepancy index (node 10). A search is then made through memory to attempt to find any analyzer which matches the input (node 11). If one is located, its number is copied into the prediction list of the previous analyzer (node 12). A check is then made to see if the pointer is within the limits of the index (node 7 again), and the program continues as outlined above.

If at node 11 no analyzer can be found which matches the input, the position of the pointer on the index is checked at node 13. If it has gone beyond either end, the program goes to node 14 in preparation for a blind move (node 15). If at node 13 the pointer is still within the limits, the program passes to node 16. Here a check is made of the peripheral retina to ensure that at least one region indicates the presence of contour. If the whole of the periphery is empty, no saccade can be computed and the program passes to node 14.

If there is contour indicated in the peripheral retina, the saccadic reflex computes which regions is to be the target (node 17). This computed peripheral target region will be recorded in the memory array as a component of a new analyzer, but first a check is made of the fovea (node 18). If the fovea is blank and nothing is recorded in the foveal feature list, a new analyzer cannot be created. If the fovea is blank, the program jumps to node 20, but if there is a foveal feature list it passes to node 19. Here the foveal feature list and peripheral target region are entered into memory as a new analyzer. Finally, an eye movement is executed to fixate the peripheral target region (node 20), and the program returns to node 1. A complete listing of the program may be found in appendix 1.

4. The influence of the discrepancy index on CYCLOPS' looking behaviour.

a) Introduction.

The length of a sequence of fixations depends on the outcomes of predicting for each fixation which analyzers might match the current input. Patterns for which all predictions match should receive only short looks; similarly, patterns for which all predictions mis-match should also receive short looks. Patterns for which there is a mixture of matches and mis-matches should receive longer looks.

The following experiment was conducted in order to show these effects and confirm that CYCLOPS behaves as expected. The aim of the experiment was to vary the analyzers and prediction lists in CYCLOPS' memory and observe the effect this had on the amount of looking at a standard pattern. This variation in the contents of memory was achieved by the prior exposure to CYCLOPS of a pattern from a set which differed in their similarity to the standard pattern. It was reasoned that prior exposure to a pattern which was very similar to the standard would allow CYCLOPS to achieve a set of predictions that would match the input when the standard pattern was scanned. This fixation sequence would not be discrepant and should be short.

The prior exposure of a pattern which was only moderately similar to the standard should have a different effect. This would result in a set of predictions of which only a few would match the input when the standard was scanned. Such a fixation sequence would be moderately discrepant and should be longer. Finally, if CYCLOPS was initially exposed to a pattern which was dissimilar to the standard, no predictions would be acquired to match the input while scanning the standard, and the fixation sequence would be extremely discrepant and short.

b) Design.

The experiment involved the presentation of a number of patterns to CYCLOPS in three separate periods, each following immediately after the other. The contents of these periods are described below.

1. Pre-training.

CYCLOPS was exposed to a series of 9 patterns (shown in figure 43) in order to establish an initial memory of analyzers and prediction lists. Experiments with infants usually involve subjects who have had some visual experience, and the pre-training provided CYCLOPS with a comparable level of experience. This initial exposure was also included to avoid conducting the experiment with a blank memory. This would have been a unique condition which would be altered as soon as learning began and might have unduly affected the results. It was felt that if CYCLOPS is to be a valid model, it should be able to demonstrate its behaviour under normal operational conditions.

The 9 patterns were exposed in randomly chosen positions. Each was shown for a period which allowed CYCLOPS to make 30 fixations after which it was removed and the next pattern shown. The patterns during pre-training were always presented in the same way so that CYCLOPS acquired the same initial memory at the end of this period.

2. Training.

Following the pre-training, CYCLOPS was shown a single pattern for a period which allowed 180 fixations to be made anywhere in the visual world. The training pattern could be either -

a) one of the standard patterns.

b) one of the patterns which differed in some way from a standard pattern.

c) a 'blank' pattern that was a control condition in which nothing was shown.

Two patterns were used as standards, and for each a set of patterns was constructed which varied in their similarity to the standard. These variations were achieved by deforming the standards with the addition or deletion of one or more small, square areas. The standard patterns and the variations are shown in figures 44 and 45.
A similar technique for generating patterns was used by Parry (1973) for configurations of dots. The rules for generating the deformed patterns are as follows -

variant 1, similar - 1 square added.

variant 2, moderately similar - 1 square deleted.

variant 3, dissimilar - 2 squares deleted.

variant 4, very dissimilar - 2 squares deleted, 1 square added.

variant 5, extremely dissimilar - an unrelated pattern.

For both standard patterns, two examples of deformed patterns were constructed at each of these levels of

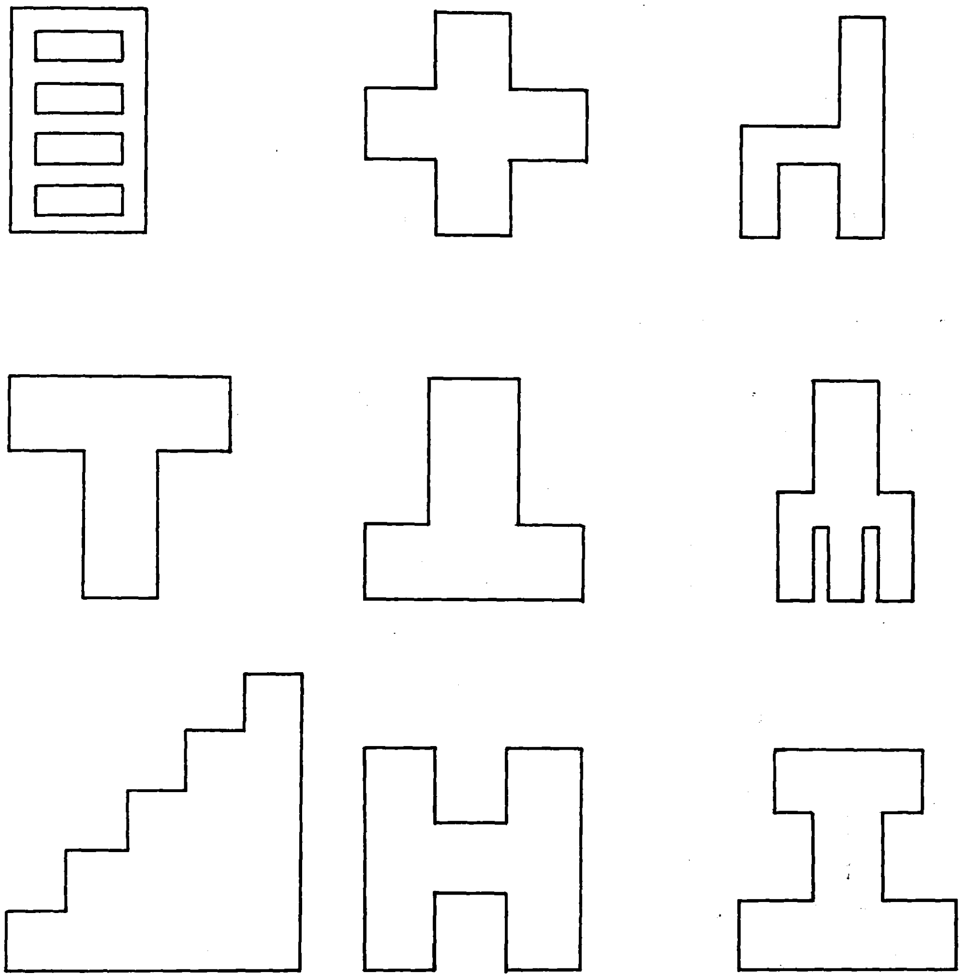


Fig. 43. The 9 patterns used to establish the initial memory during pre-training.

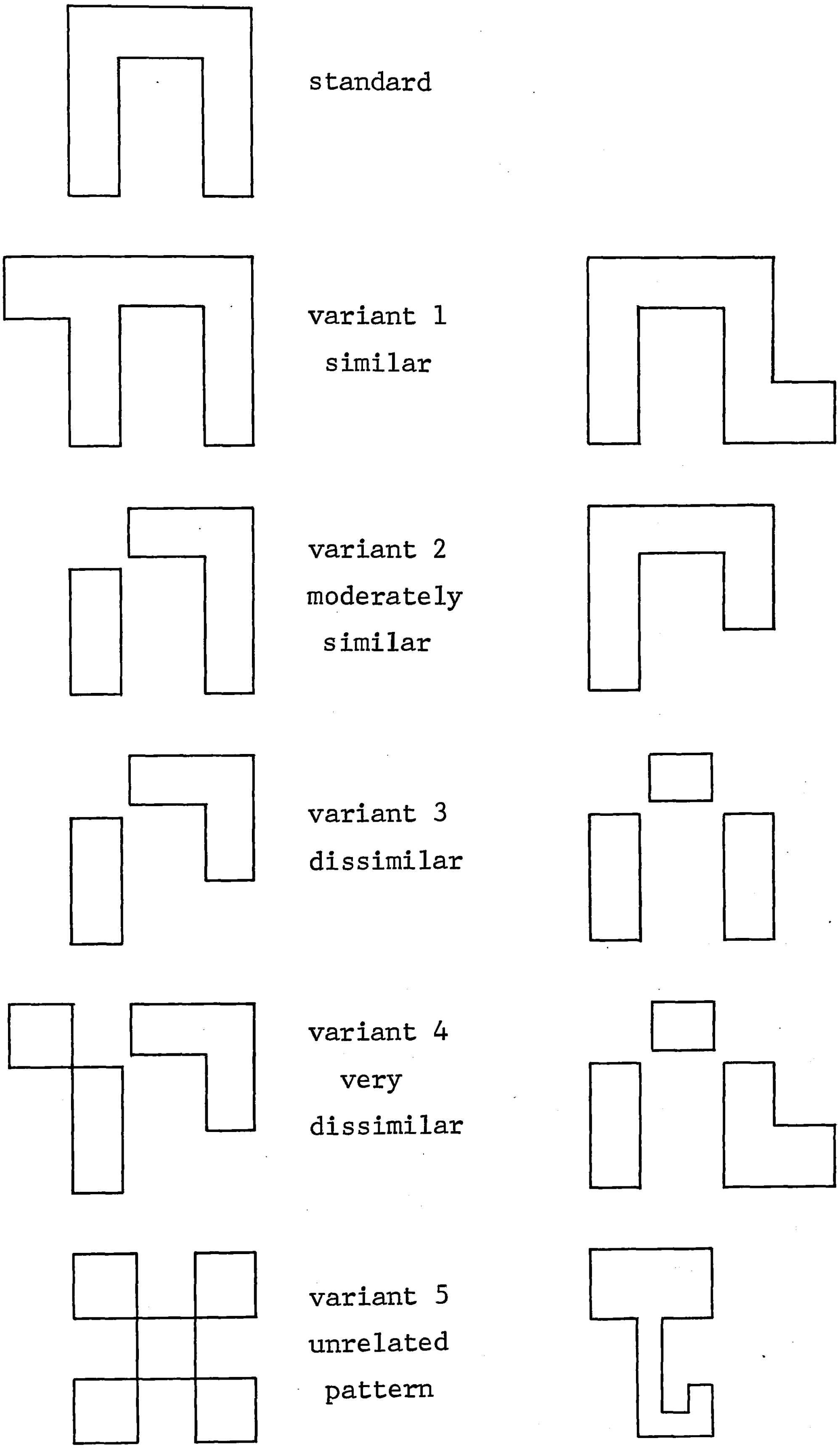


Fig. 44. Standard pattern in first experiment and variations generated by deforming it.

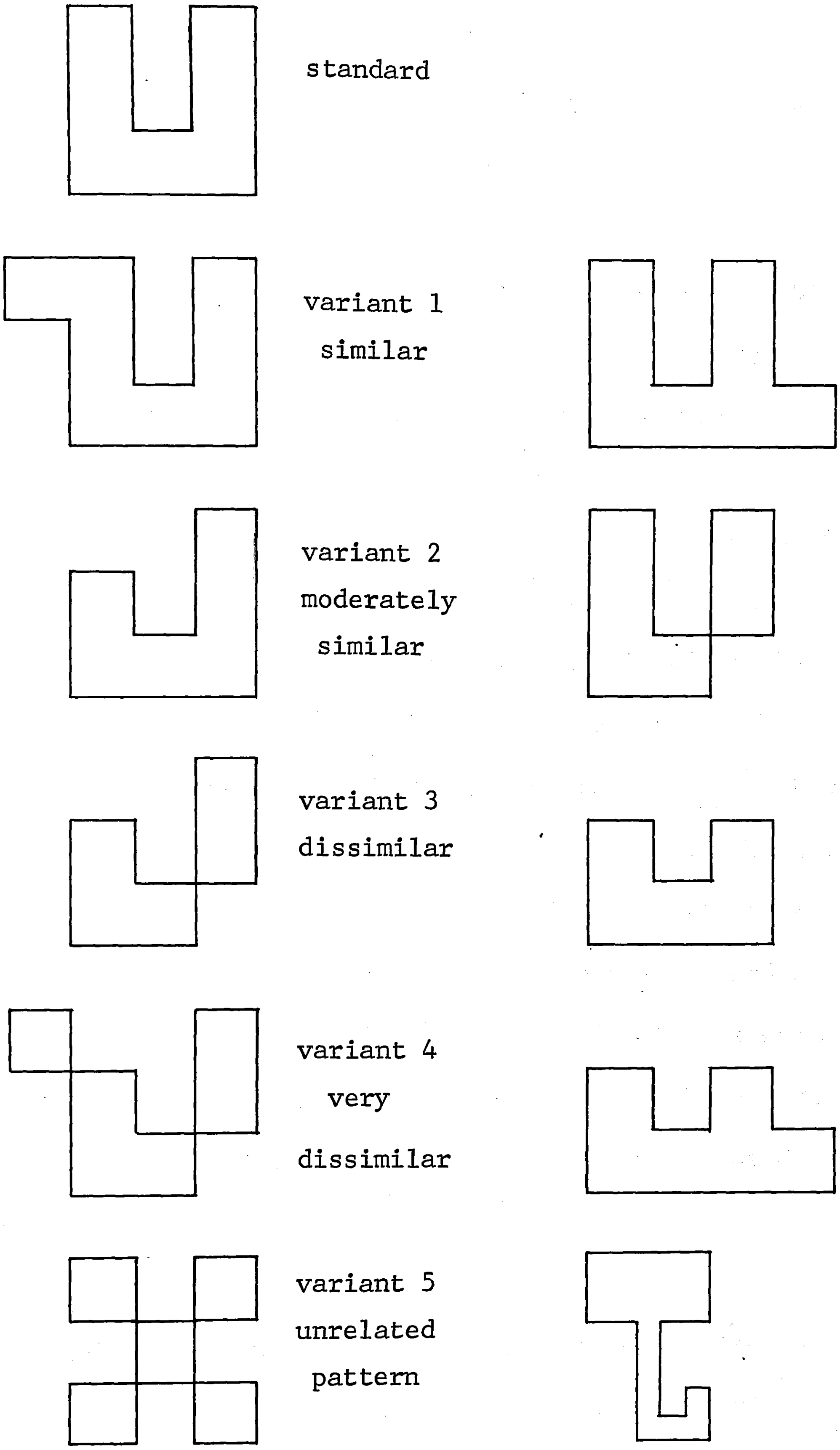


Fig. 45. Standard pattern in first experiment and variations generated by deforming it.

similarity. The variations show a progressive change from similarity to dissimilarity as more changes are made to the standard pattern.

The 180 fixations of the training period were divided into 6 blocks of 30 fixations. When each block had been completed, the training pattern was moved to a new randomly chosen position in the visual world.

3. Testing.

After the training period, CYCLOPS was shown a single pattern for a period lasting 180 fixations. This test pattern was always the standard which related to the pattern shown during training. The pattern was kept in the same location throughout the testing period. For the purposes of analysis, the 180 fixations of the test period were divided into 6 blocks of 30 fixations each.

A total of 24 experimental sessions were conducted in this manner, 2 in which the standard patterns were shown during training, 20 in which the variations were shown, and 2 in which 'blank' patterns were exposed in the training period.

c) Measures.

Several different measures were used to record the amount of looking at the standard pattern in the testing period. It is impractical to attempt to use a temporal measure with a computer program, but it is possible to translate time into the number of fixations made during a sequence. All the measures of looking used with CYCLOPS interpret 'length of looking' in terms of the number of fixations made while looking.

Total amount of looking.

This is the simplest measure and consists of the total number of fixations made on a pattern during a block of 30 fixations. Any fixations made elsewhere in the visual world (eg. during blind moves) are not included. This measure provides a general indication of the amount of looking at a pattern, but does not give much detailed information about CYCLOPS' behaviour. It does not indicate whether all fixations occurred in one long sequence or several short sequences. This criticism also applies to the temporal measure of infant looking (Cohen, 1973).

Mean length per look.

This is a more useful measure where a look is defined as an unbroken sequence of fixations on a pattern. A look may be terminated either by a blind move or by reaching the end of a block of 30 fixations. The latter may tend to reduce the value of the score particularly if a long sequence is interrupted by the end of a block. For this reason the convention was adopted that only a sequence of 3 or more fixations would be counted as a look.

Length of first look.

The length of the first look at a pattern has been found to be a good measure of the attention-eliciting power of a stimulus with infants (McCall, 1971). Since it is concerned with the very first look at a pattern in a block of fixations, this measure might be expected to reveal most about the effects of discrepancy on looking. Measures involving later looks at patterns may be contaminated by learning established during the initial looks.

d) Results.

Although the experiment was conducted essentially with one subject, some generality of the results was achieved by using a number of different patterns. The results which follow are the means of the individual scores for looking at the standards obtained following the different training conditions.

The scores for the length of the first look at the standard during the test period are shown in figure 46. The solid line shows the length of first look during block 1 of the test period (fixations 1-30), and the broken line is the mean length of first look for all 6 blocks of the test period.

The influence of the different kinds of training is apparent in figure 46, though the effects are only shown for the first block of fixations. These effects are lost during the later blocks of the test period, and the means for all 6 show only slight differences. The discussion of

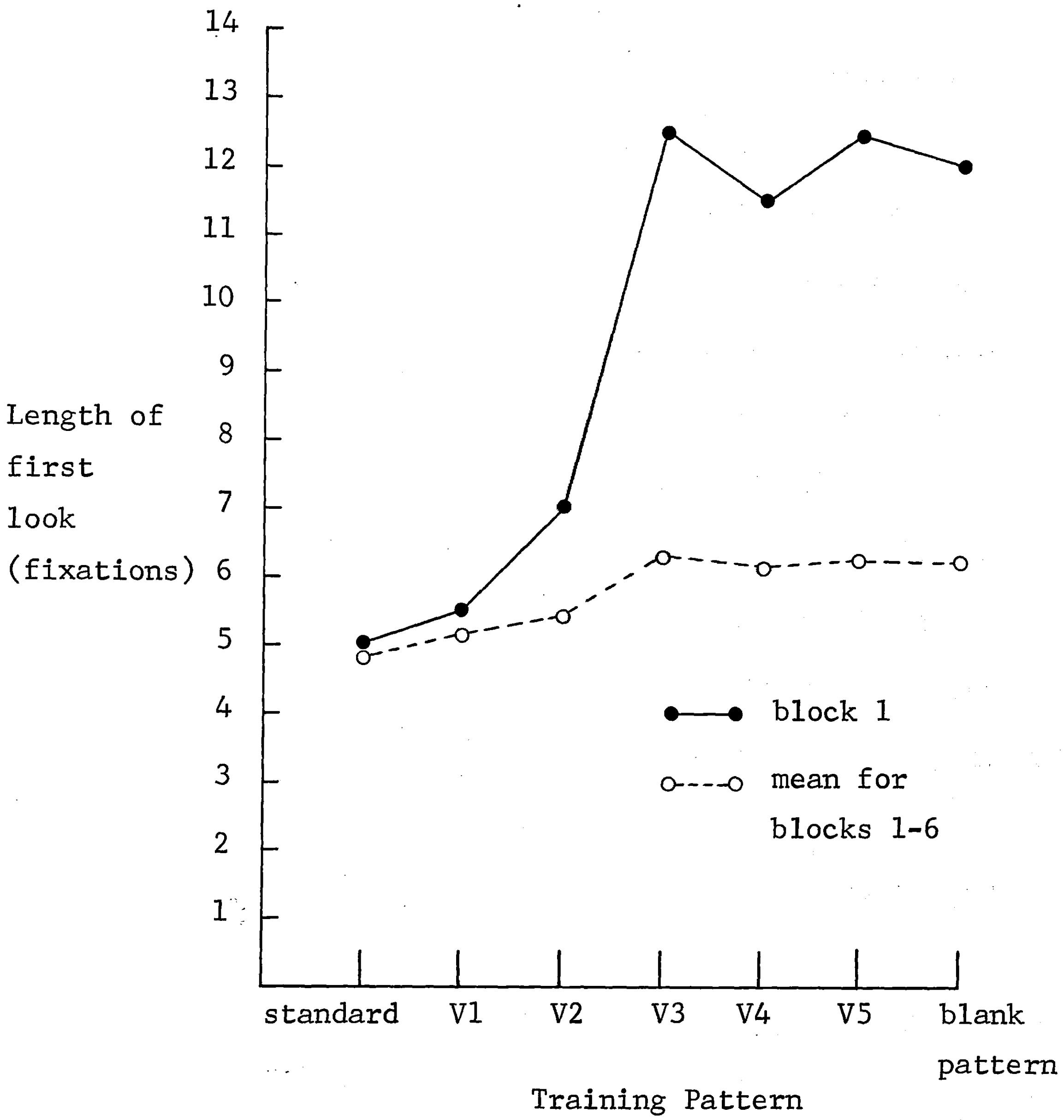


Fig. 46. First experiment; length of first look at standard during testing after exposure to training pattern.

the results will focus on the first block.

The shortest first look was produced after training with the standard pattern. This result was predicted, and CYCLOPS was able to acquire a set of predictions after training which resulted in a sequence of matches when the standard was fixated. As the training pattern became less similar to the standard, the length of the first look in the test period became longer. Training with the variant 1 patterns produced slightly longer first looks at the standard, and after training with the variant 2 patterns they were longer still. These results were also predicted as CYCLOPS acquired a set of predictions during training of which only some produced matches when the standard was examined. These sequences of fixations were moderately discrepant and therefore longer.

This increase in the length of the first look at the standard continued following training with the variant 3 patterns, but the length remained long even after training with the patterns which were very dissimilar from the standard. This result was not expected as CYCLOPS should not have acquired any matching predictions during training with these patterns. The reason for this unexpected finding is shown by the result after training with a blank pattern. The first look at the standard was also long in this condition, but there was no opportunity to acquire any matching predictions for the standard. The explanation is that the initial memory established during the pre-training period contained some predictions which produced matches when the standard was fixated. This resulted in a first sequence of fixations which was moderately discrepant, and accounted for the long first looks after training with the blank pattern and the patterns which were very dissimilar to the standard.

Similar results are shown for the mean length per look (figure 47) and the total length of looking (figure 48), though the effects are not so great with these measures. Training with the standard pattern produced the least amount of looking at the standard in the test period, but this increased as the training pattern became less similar to the standard. The amount of looking is also high with these measures for the blank and dissimilar training patterns, and the influence of the pre-training memory is again apparent.

For all measures, these effects are only shown during the first block of fixations. The means for all 6 blocks reveal little difference according to training conditions. The reason for this was that CYCLOPS acquired a matching set of predictions for the standard in the early stages of the test period with the result that further looks at the standard were not discrepant and remained short. Since

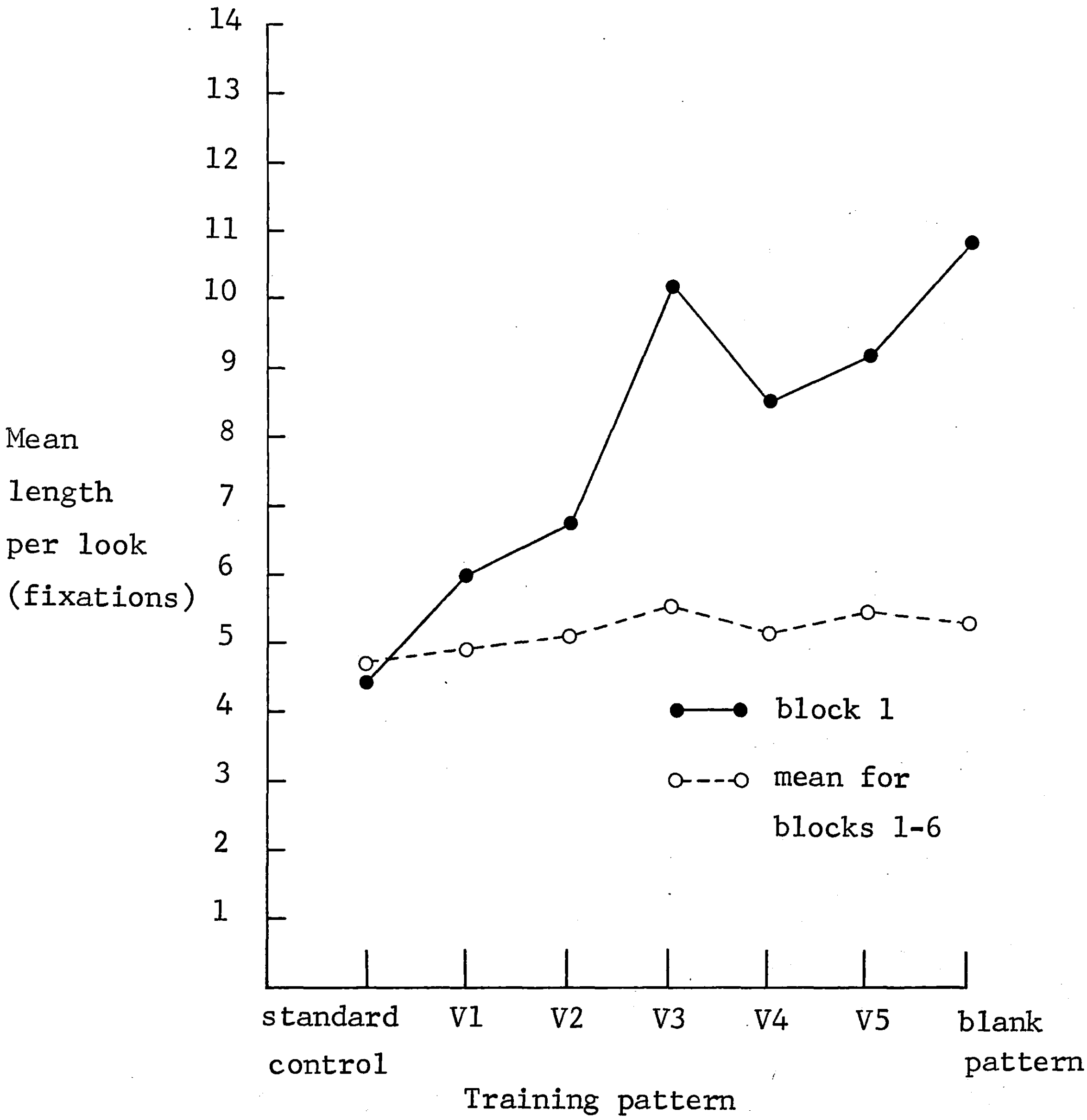


Fig. 47. First experiment; mean length per look at standard during testing after exposure to training pattern.

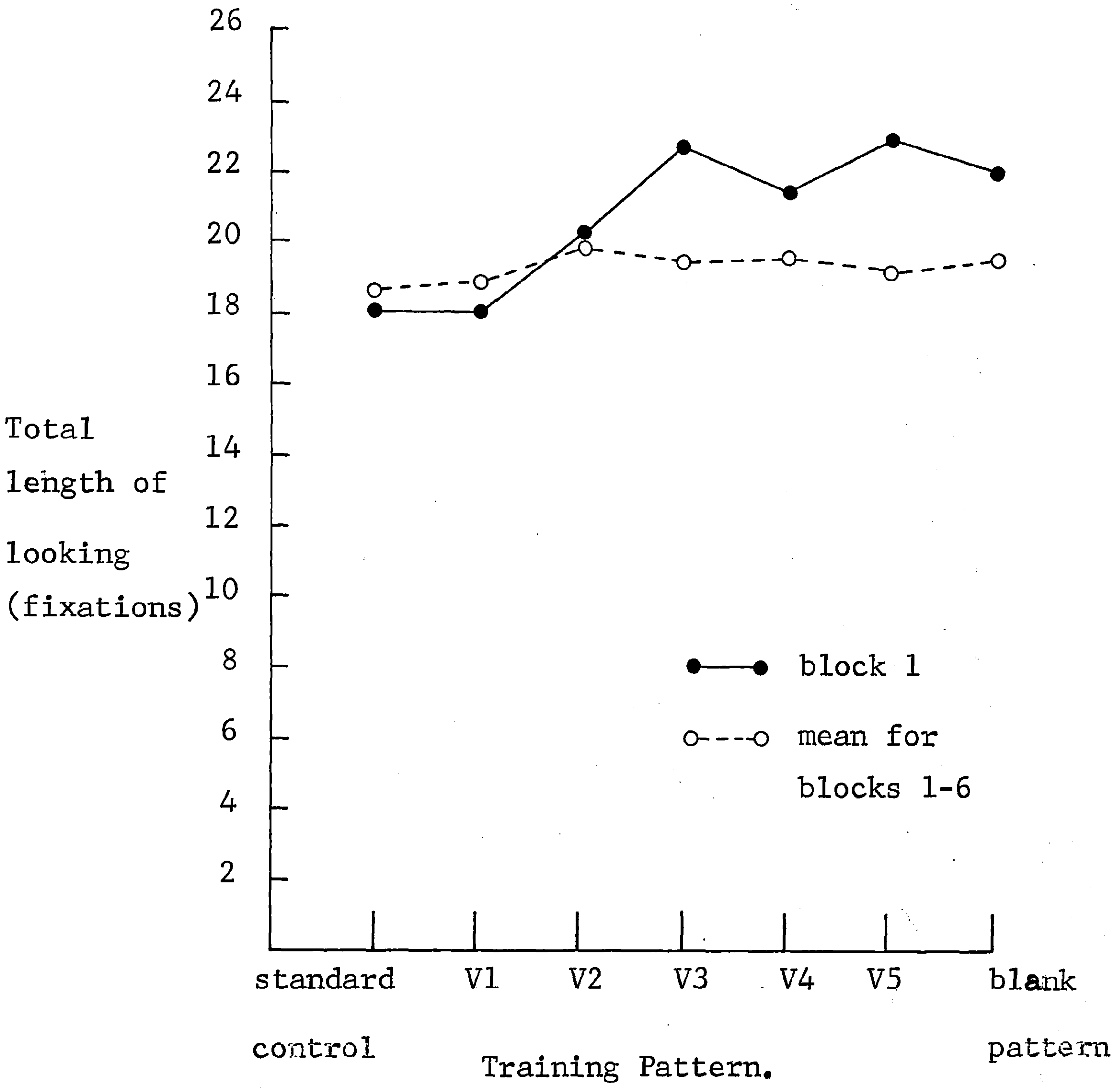


Fig. 48. First experiment; total length of looking at standard during testing after exposure to training pattern.

the looks during the later blocks were all of the same length, the mean scores for the 6 blocks failed to produce large differences.

e) Conclusions.

The results of this experiment only partially confirmed the predictions. Training with a standard pattern produced the least looking and shortest fixation sequences in the test period. Training with patterns similar to the standard produced longer fixation sequences. However, training with very dissimilar patterns did not result in short fixation sequences because of the extra influence of the initial, pre-training memory. If the expected results had been achieved, the curves for each of the measures would have taken the form of an inverted U. A number of infant experiments have used a similar design and also failed to produce such a curve (eg. Parry, 1973). It is possible that the reason for this may be the same as for CYCLOPS. Even though an infant is exposed to a stimulus which is very dissimilar to a standard stimulus, he may still look longer at the standard because he finds it moderately discrepant with the memory he brought to the experimental situation.

f) A second experiment.

The failure to obtain short fixation sequences after training with the dissimilar patterns was due to the pre-training experience providing CYCLOPS with a number of matching predictions for the standard pattern. It should be possible, however, to obtain the predicted results if the standard pattern was one for which the pre-training memory did not contain any matching predictions. A second experiment was conducted using this type of standard pattern.

Two such patterns were discovered by a process of trial and error. CYCLOPS was shown the pre-training patterns, and then a potential standard pattern. This was selected as a standard if it received only short looks because each prediction mis-matched with the input. The two standard patterns for which there were no matching predictions in the pre-training memory are shown in figures 49 and 50. For both standards, two variations were constructed at each of the levels of similarity.

The experiment was repeated exactly as outlined above using these two further standard patterns and their variations. The results are shown in figures 51 to 53 though the effects of training conditions are only apparent in the scores for the first block of fixations of the test period. The discussion of the results of this second experiment will concentrate on these scores.

The length of the first look at the standard (figure 51) produced an inverted U relation with the type of training

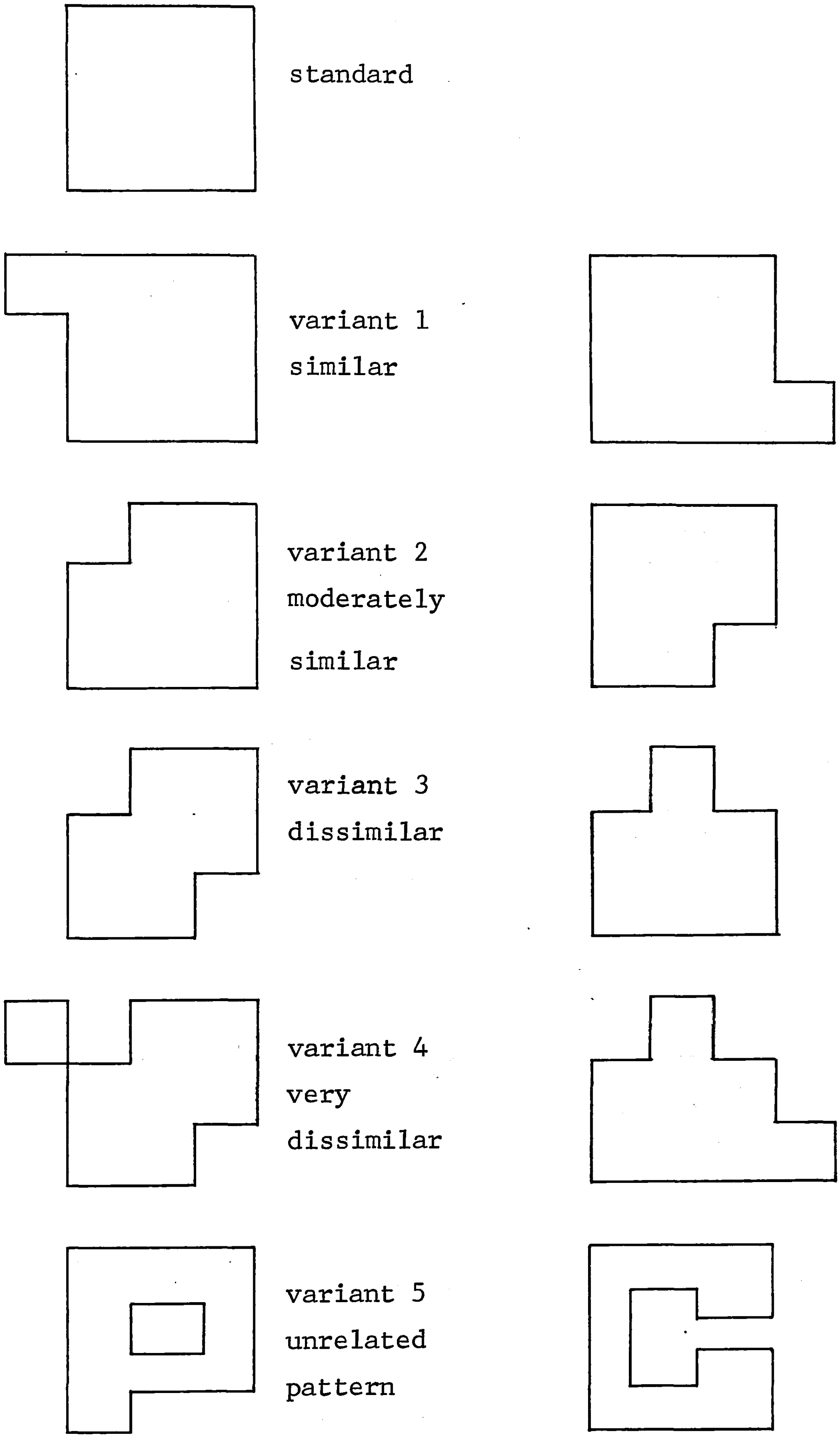


Fig. 49. Standard pattern in second experiment and variations generated by deforming it.

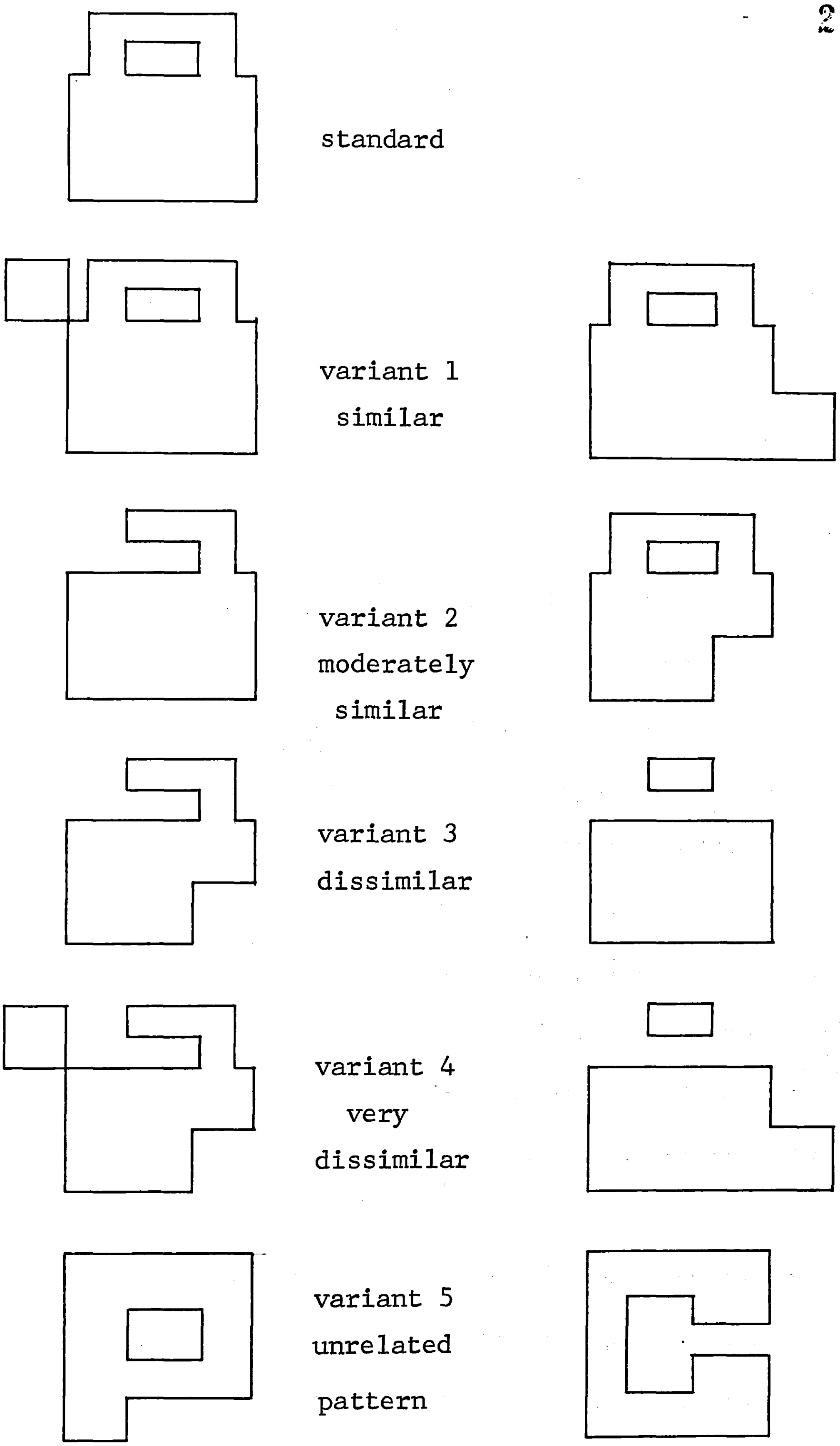


Fig. 50. Standard pattern in second experiment and variations generated by deforming it.

pattern. As in figure 46, training with the standard resulted in a short first look at the standard during testing. Training with the variants 1 and 2 produced much longer first looks at the standard. These scores are higher than the comparable ones in figure 46, and the reason lies with the pre-training memory. The length of a sequence of fixations depends on how long the pointer can be maintained between the two ends of the discrepancy index. In the first experiment, CYCLOPS acquired matching predictions from the pre-training patterns and from the training patterns. In the second experiment, CYCLOPS acquired fewer matching predictions as the only source was the training patterns. Because there were more matches in the first experiment, the pointer tended to cross the lower end of the discrepancy index sooner than in the second experiment. As a result, training with variants 1 and 2 produced shorter first looks in the first experiment, while in the second the pointer was able to remain for a longer period between the ends of the index and the looks contained more fixations.

Training with variants 3 4 and 5 and the blank pattern also resulted in short first fixations of the standard. This contrasts with figure 46 where the scores for these training conditions are high. In this second experiment there were no matching predictions in the pre-training

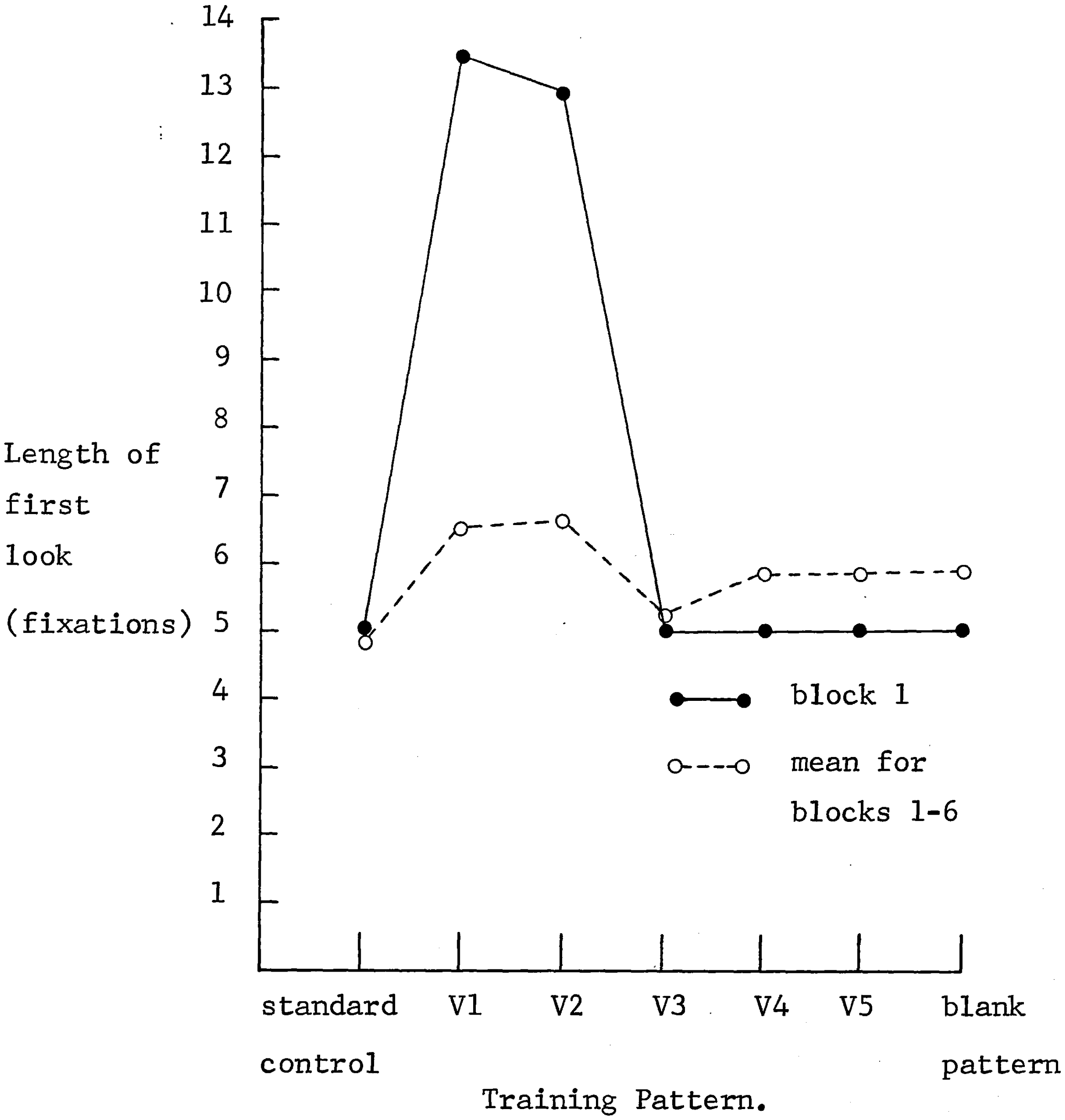


Fig. 51. Second experiment; length of first look at standard during testing after exposure to training pattern.

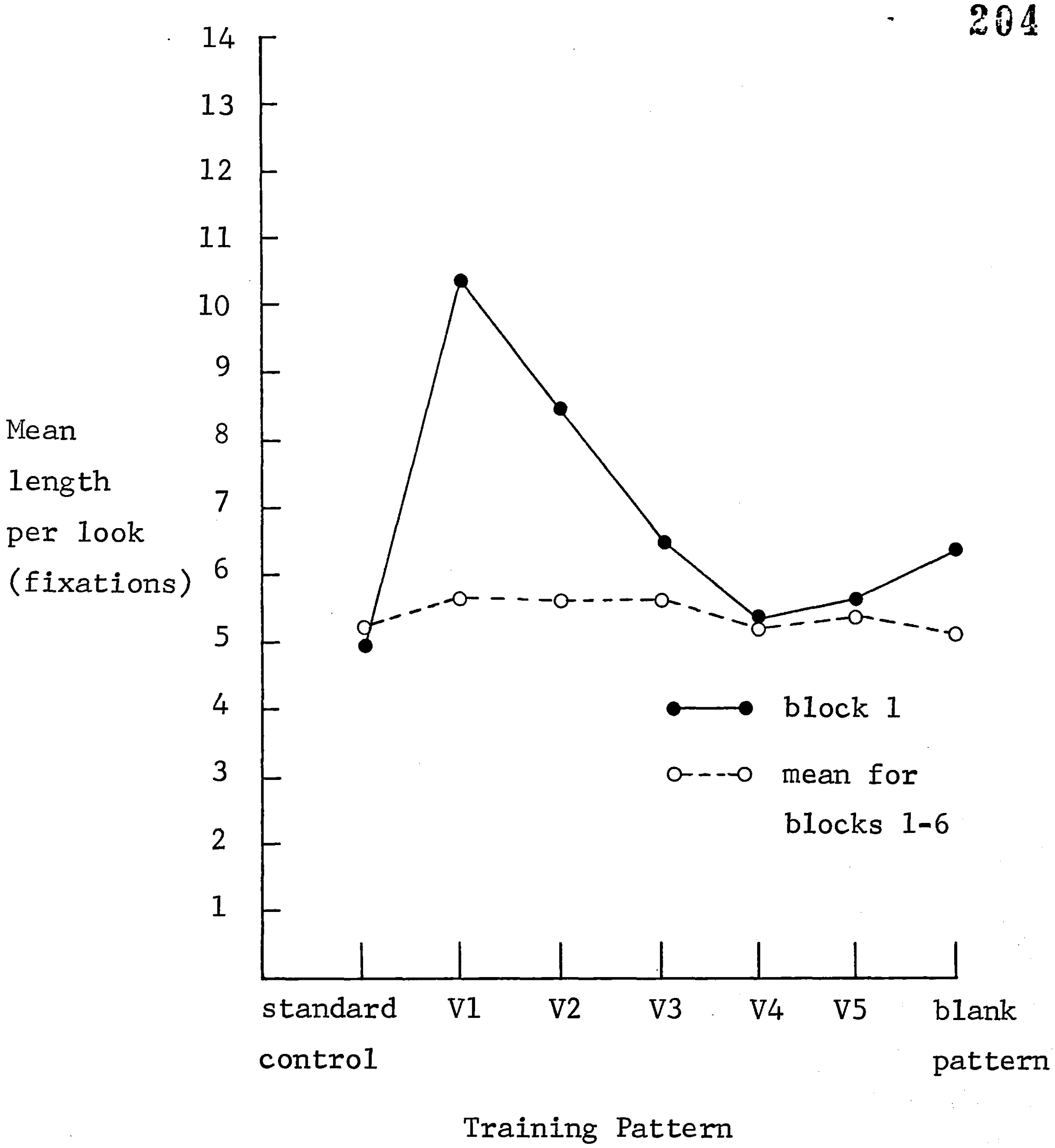


Fig. 52. Second experiment; mean length per look at standard during testing after exposure to training pattern.

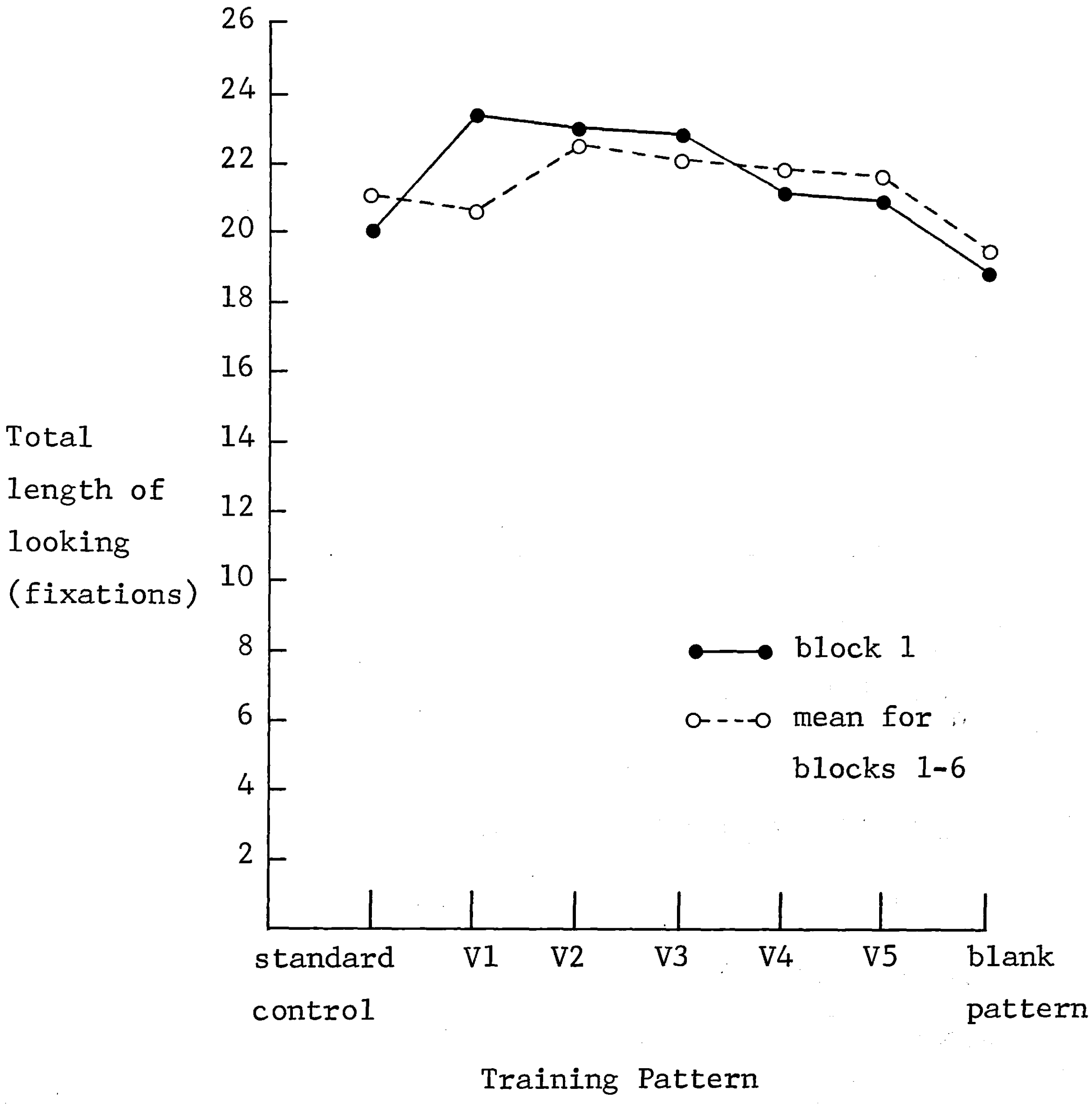


Fig. 53. Second experiment; total length of looking at standard during testing after exposure to training pattern.

memory, and none were acquired during training because the patterns were very dissimilar to the standard. As a consequence, each fixation during testing resulted in a mis-match and the sequences were short.

The same effects are shown by the mean length per look (figure 52) and total length of looking (figure 53), though as in the first experiment the effects are not as great with these measures.

g) Discussion.

The results of these experiments demonstrate how CYCLOPS reacts to the amount of discrepancy in a sequence of fixations between the predicted input and the input which was actually encountered. The amount of discrepancy which occurred was manipulated by training CYCLOPS with patterns varying in their similarity to the standard. When the training pattern was identical to the standard, no discrepancy was encountered and the fixation sequences in the test period were short. When the training pattern was similar to the standard, moderate discrepancy was encountered as only some predictions matched, and the fixation sequences were longer. It was also found that the pre-training could affect the length of the sequences. In the first experiment pre-training provided some matching predictions for the standard which reduced the length of the fixation sequences after training with the similar patterns. In the second experiment the pre-training did not supply any matching predictions, and the sequences were longer following training with the similar patterns.

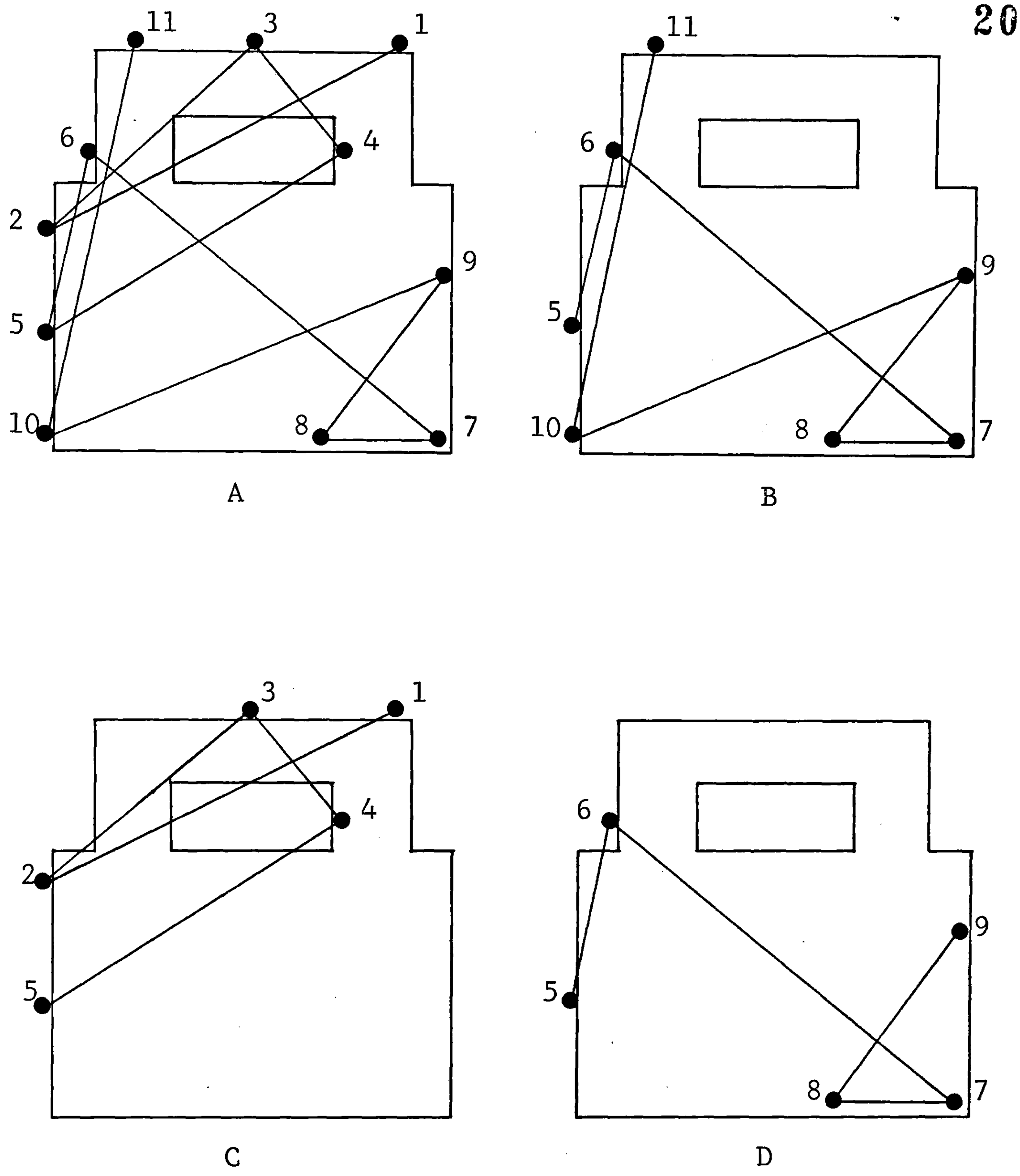
It was expected that training with patterns which were dissimilar to the standard would not allow matching predictions to be acquired and the sequences during the test period would be short. This was not the result in the first experiment because the pre-training interfered and was a source of matching predictions. In the second experiment this source was excluded by selecting patterns as standards for which no pre-training predictions resulted in matches. When this was done it was shown that training with a pattern dissimilar to the standard did not allow CYCLOPS to acquire any matching predictions. The fixation sequences on the standard in the test period were then extremely discrepant and short in length.

One significant finding which has not been covered is the effect which the discrepancy index has on scanpaths. When a sequence of fixations is moderately discrepant, CYCLOPS takes a long look and makes many fixations. While scanning is in process, CYCLOPS acquires new predictions so that a further look at a pattern results in an increase in the number of matching predictions. This means that with repeated looks at a pattern, the amount of discrepancy will decline and the length of each look will become correspondingly shorter.

A series of looks which illustrates this is shown in figure 54. In A the fixation~~s~~ sequence was moderately discrepant and lasted for a total of 11 fixations before a blind move occurred. The next look is shown in B, and because some matching predictions were acquired previously there was less discrepancy and the look was shorter, lasting for 7 fixations. The two succeeding looks (C and D) reveal that all predictions correctly matched the input, and with no discrepancy both lasted for 5 fixations.

Although there is a decline in the length of the sequences from 11 to 5 fixations, careful examination of the scanpaths shows that each of the paths in B, C and D are components of the original which was followed in A. This is the kind of behaviour CYCLOPS is expected to produce since recognition is demonstrated by short looks and the recurrence of scanpaths. However, because the scanpath in A was long, it was possible for both the scanpaths in C and D to be components of the initial path, yet to have nothing in common with each other.

If human subjects behave in a similar way as CYCLOPS, this could account for Noton & Stark (1971a, 1971b) failing to detect the recurrence of scanpaths for certain pictures. The results obtained by Furst (1971) support this interpretation as the number of fixations a picture



The initial scanpath is shown in A, and the pattern received 11 fixations in the order shown. The next look is shown at B, and lasted for 7 fixations. The next two looks are shown at C and D, each lasting 5 fixations. The fixation numbers in B, C and D refer to the initial scanpath in A. All scanpaths are components of A, but each has little in common with the others.

Fig. 54. The decline in the length of recurring scanpaths with repeated looking.

received declined with its repeated presentation. Noton and Stark exposed their pictures initially for 20 seconds, but subsequently they only had 3 recognition exposures of 5 seconds each. The example from CYCLOPS in figure 54 suggests that for certain pictures, more than 3 exposures would be needed to detect the recurrence of scanpaths.

CHAPTER 7.

THE SIMULATION OF INFANT LOOKING BEHAVIOUR BY CYCLOPS.

1. Introduction

The discussion of CYCLOPS' behaviour up to this point has been concerned with showing how the various parts of the program act to permit the learning and recognition of patterns. Chapter 5 described the process of pattern learning in which analyzers and prediction lists are acquired while a pattern is scanned. When the learning is completed, CYCLOPS provides evidence of recognition by repeating the original scanpath when scanning the pattern again. In Chapter 6 the operation of the discrepancy index in controlling the length of a sequence of fixations was discussed. When the pattern which is scanned produces a sequence of fixations which is moderately discrepant with the contents of memory, the sequence will be long. As more predictions are acquired and discrepancy declines because predictions match the current input, the sequence becomes shorter.

In this chapter it will be shown how CYCLOPS is capable of producing the same looking behaviour as infants by simulating three experiments conducted with infants. Each is concerned with the infant's ability to learn and recognize patterns, and they all use the same basic strategy though modified in various ways. This strategy was first proposed by Fantz (1956), and consists of showing patterns and recording the amount of looking they receive. If any patterns are looked at differently than the others (ie. shorter or longer), it may be concluded that the infant is capable of discriminating them. If one of the patterns has been shown before to the infant (ie. it is familiar) and another pattern is seen for the first time, the typical response is to look less at the familiar one and more at the new pattern (Bond, 1972). This difference in looking may then be taken as evidence of recognition of the familiar pattern. Of course, this is the kind of behaviour which the discrepancy principle seeks to explain, but it is important to note that none of the experiments which follow were specifically concerned with this principle. This means that the simulations may be regarded as showing CYCLOPS' ability to mimic infant looking behaviour, and as a test of the discrepancy principle as an explanation of such behaviour.

The first experiment by Fantz (1964) demonstrated the infant's preference for new over familiar patterns, but such a preference develops over time and is not shown by very young infants. In section 4 of Chapter 3 it was suggested that the discrepancy principle would predict such a developmental preference for novelty, and the simulation represents a test of this prediction. The second experiment by Caron and Caron (1969) was concerned with the decline in the amount of looking a pattern received when it was shown repeatedly. This experiment also examined the effects on looking of the level of complexity of the pattern, but this aspect was not included in the simulation. The final experiment by Fagan (1971) studied the ability of infants to recognize a pattern immediately after seeing it and following a delay. This experiment was concerned with the length of time an infant could retain a memory for a pattern.

2. Simulation of the experiment by Fantz (1964).

a) The infant study.

Design.

The infants studied ranged in age from 1 to 6 months, and were divided into 4 groups of 1-2 months, 2-3 months, 3-4 months and 4-6 months. The stimuli were 11 magazine photos which were presented in pairs for 1 minute, 10 such exposures making an experimental session. One of the pictures in the pairs was kept constant and was shown to the infants at each exposure. The other picture in the pair was changed with each new exposure, and this will be referred to as the variable picture. At the end of an experimental session the infants had received 10 exposures of one picture, but only 1 exposure of each of the remaining

10 variable pictures.

In order to control for any preferences which might have arisen from seeing the constant picture in the same position, the positions of the constant and variable pictures were exchanged half-way through an exposure. The amount of looking at the patterns was recorded by an observer who could see the reflection of the fixated picture in the infant's cornea. The total time which was spent looking at each of the constant and variable pictures was computed for the 10 separate exposures, but the number of individual looks and their mean duration was not reported.

Results.

In the Fantz (1964) paper, the results were expressed as the percentage of the overall looking time spent fixating the constant picture. The youngest group of infants showed no preferences for either type of picture and looked approximately 50% of the time at both the constant and variable. This equal division of looking time was maintained across all 10 successive exposures, and there was no decline or increase in looking at the constant.

The 3 older groups of infants (all above 2 months) produced a gradual decline in looking at the constant, beginning at 50% of the total, but falling to a level of 30%-35% by the final exposure. These results are shown in figure 56b where the curve for the younger infants is taken from Fantz (1964), and the curve for the older infants is derived from results reported in Fantz (1966). Since all 3 groups of older infants produced similar curves, the results in figure 56b for infants older than 2 months are the mean percentage scores.

These results indicate that infants of 2 months or more are capable of recognizing a picture which is repeatedly exposed and reveal this by looking less at such a picture relative to one which is new. Infants younger than 2 months do not produce such a decline in looking, but it cannot be concluded that they are unable to recognize the constant picture. They may have achieved this, but were simply unable to vary their distribution of attention to the constant and variable pictures. However, these results do point to a developmental change in looking behaviour in which infants younger than 2 months do not indicate recognition by means of attentional preferences, but infants older than 2 months look progressively less at a picture which is repeatedly exposed.

b) The simulation with CYCLOPS.

Design.

The infant results suggest that the main difference between the groups of infants was age, with 2 months being the significant division. For the purposes of simulation with CYCLOPS, it was reasoned that the primary distinction between these infants was the amount of visual experience they had received. This is not to discount the possibility of other maturational factors (for example, the ability to focus on distant objects which appears at about 2 - 3 months, Haynes, White and Held, 1965), but such considerations are outside the capability of CYCLOPS and would only complicate the model.

In order to simulate these two groups of infants, the experiment was run under two conditions. The first corresponded with the younger infants of 2 months or less, and CYCLOPS began each experimental session with a blank memory containing neither analyzers nor prediction lists. This assumed that the young infants had experienced negligible visual stimulation. The second condition, corresponding with the older infants of more than 2 months, provided CYCLOPS with a memory containing a number of analyzers and prediction lists. This will be referred to as the 'primed' memory condition, as opposed to the 'blank' memory simulation of the younger infants. This memory was obtained by exposing the 9 patterns illustrated in figure 43, and was identical to the initial memory established in the pre-training phase of the experiments reported in Chapter 6. CYCLOPS began each primed memory session with exactly the same memory.

11 patterns were selected from the library (see figure 55), and the same set was used for all experimental sessions.

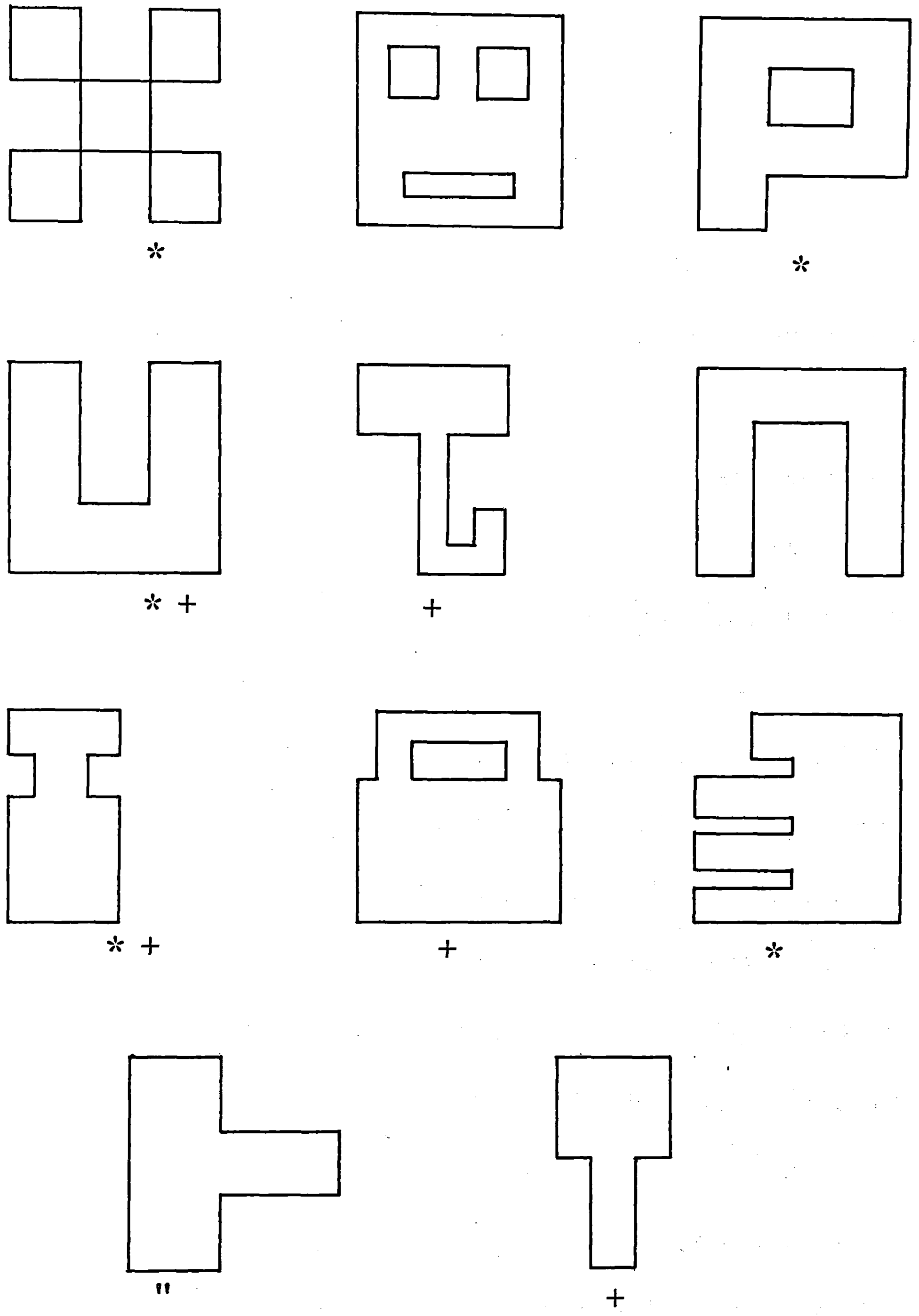


Fig. 55. Patterns used in the simulation of the experiment by Fantz (1964). Constant patterns indicated by *.

All these patterns except the one marked " were used in Caron & Caron (1969) simulation. Test patterns in that simulation indicated by +.

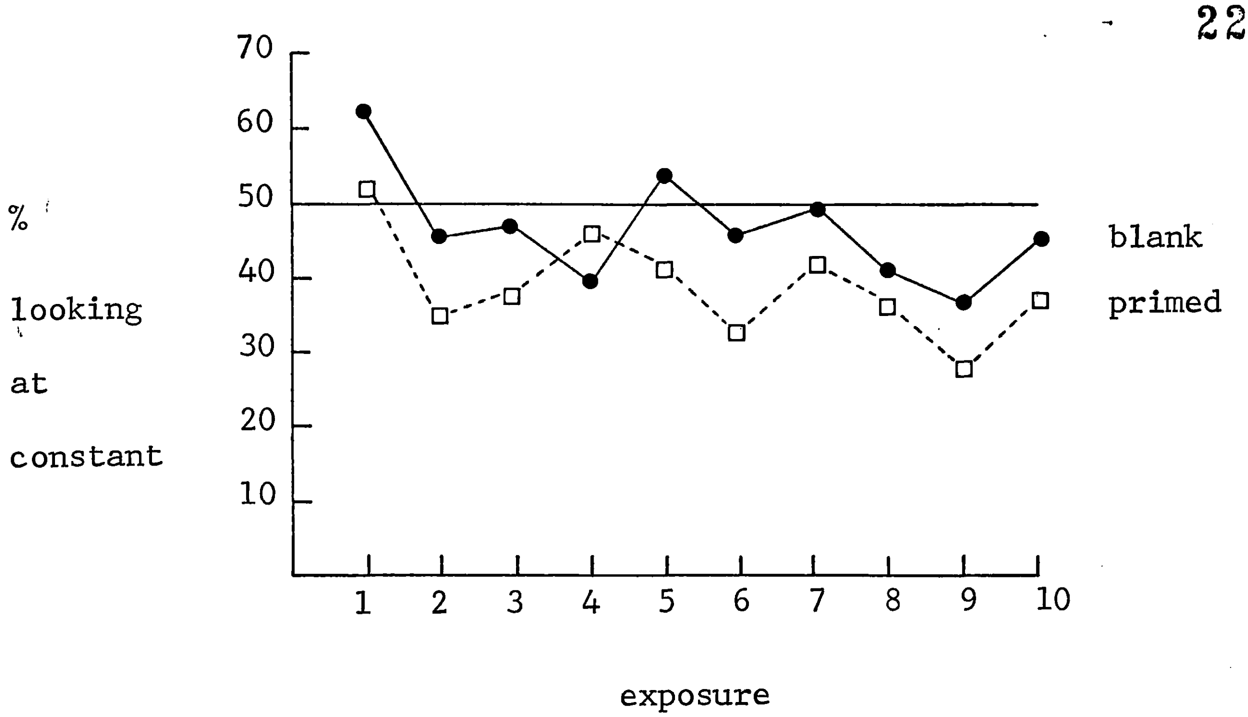
They were exposed to CYCLOPS in pairs, one pattern initially being randomly chosen as the constant and paired with each of the remaining 10 patterns. These pairs of patterns were presented in 10 exposures to CYCLOPS. An exposure permitted CYCLOPS to make 30 fixations anywhere in the visual world, and on completion the patterns were removed and the next pair substituted. The patterns were placed so that CYCLOPS could not fixate both foveally, but could detect one peripherally while the other was fixated with the fovea.

On the first exposure the constant pattern was placed at the left with the variable pattern at the right. These positions were alternated with each succeeding exposure of a pair and not half-way through an exposure as in the infant study. If this had been carried out, it would have meant exchanging the patterns after CYCLOPS had made only 15 fixations and this could have affected the amount of looking, especially if the exchange interrupted a look. It would have been possible to double the length of an exposure and make the exchange half-way through, but this would have doubled the running time of the experiment. In order to keep it as short as possible this compromise was adopted. It should not have affected the results unduly as CYCLOPS does not have position preferences.

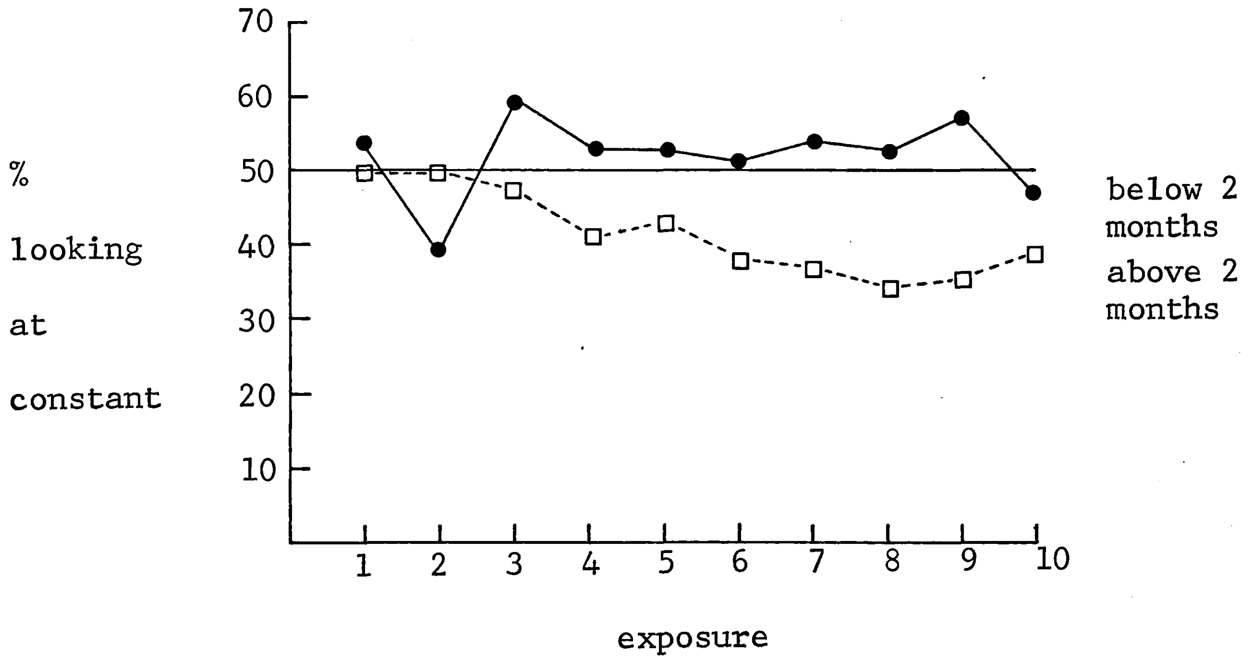
A total of 5 sessions were conducted with a different pattern used as the constant in each and the order of presentation of the variable patterns randomly determined. The patterns used as constants are indicated with a star in figure 55. The same 5 sessions were conducted under the two conditions of blank and primed memory so that each result is the mean of 5 individual scores.

Results.

The amount of looking at the two kinds of patterns can be recorded with several measures, though Fantz only reported the percentage of the total looking time spent fixating the constant pattern. The total amount of looking for CYCLOPS is measured by counting the number of fixations which were made on the patterns and ignoring any made during blind moves on blank areas of the visual world. The percentage of this value spent looking at the constant pattern is shown for each exposure in figure 56a. When CYCLOPS began with a blank memory, looking was divided fairly equally at a 50% level between the constant and variable patterns, though the final 3 exposures suggest the constant was looked at less. With a primed memory, CYCLOPS looked equally at the two types of pattern in exposure 1, but then showed evidence for recognition of the constant as the amount of looking it received fell to about 30-35%. For each exposure except number 4, the constant was looked at less when CYCLOPS had a primed memory instead of a



a) Simulation with CYCLOPS



b) Infant results (adapted from Fantz, 1964 and 1966)

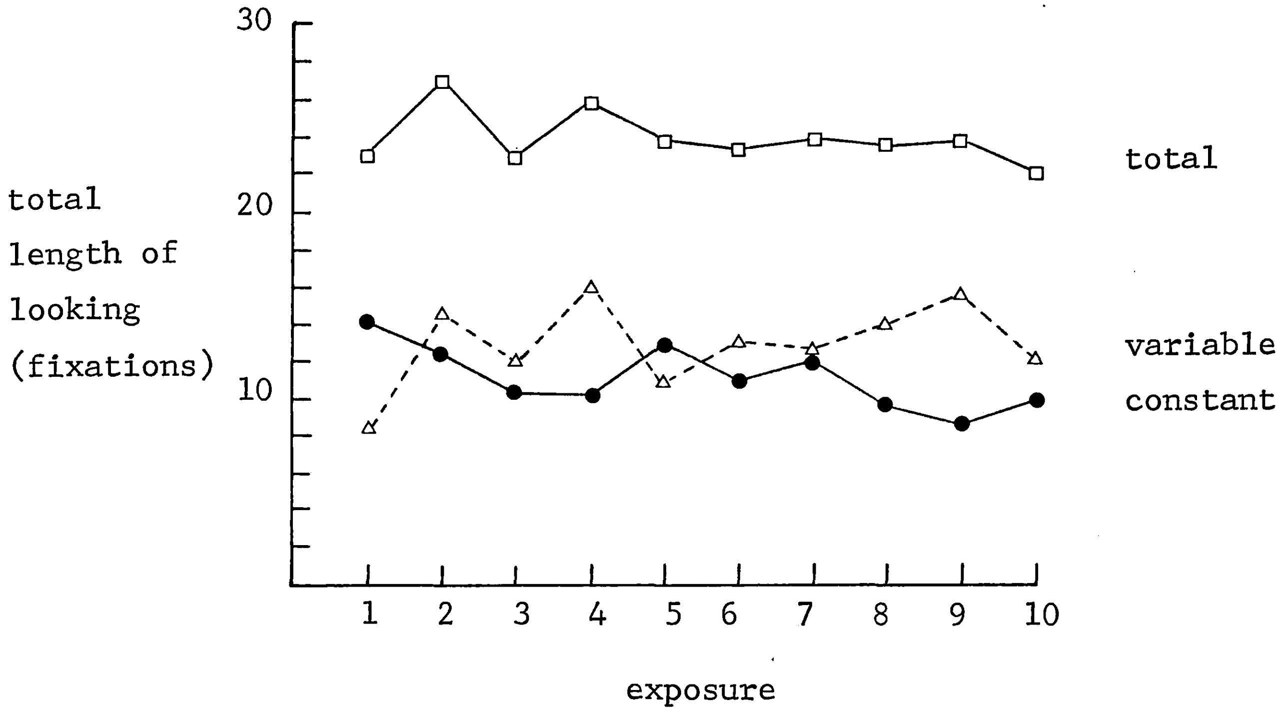
Fig. 56. Percentage of total looking at constant pattern across 10 exposures.

blank one.

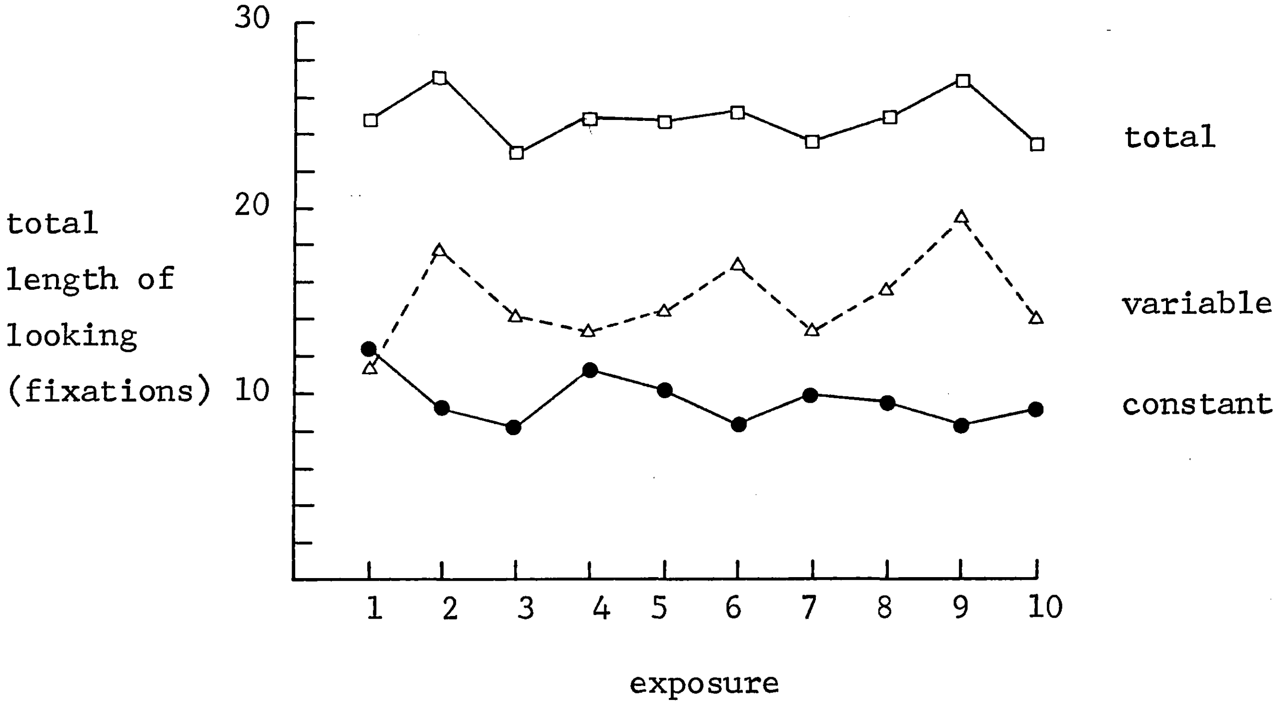
For purposes of comparison, the results Fantz obtained are shown in figure 56b. Here also, for every exposure except the first two, the older infants looked less at the constant pattern than the young ones. However, the distinction between these curves is clearer than those obtained with CYCLOPS, and the simulation suggests a decline in looking at the constant for the later exposures with a blank memory. The influence of the primed memory can be seen in figure 56a, but it is not as clear cut as might be expected.

In figure 57, the total amount of looking at the two kinds of patterns is shown for CYCLOPS with blank and primed memories. For both, the total length of looking was the same and remained at a fairly constant level for all 10 exposures. With a blank memory, the amount of looking at the variable patterns was similar to the amount for the constant, and the two curves are close together. With a primed memory, CYCLOPS showed an almost immediate difference, looking far less at the constant so that the curves are much further apart.

These differences are also revealed with other measures. Figure 58 shows the curves for the mean length of each look at the two types of patterns, and figure 59 illustrates the curves for the length of the first look. On both these

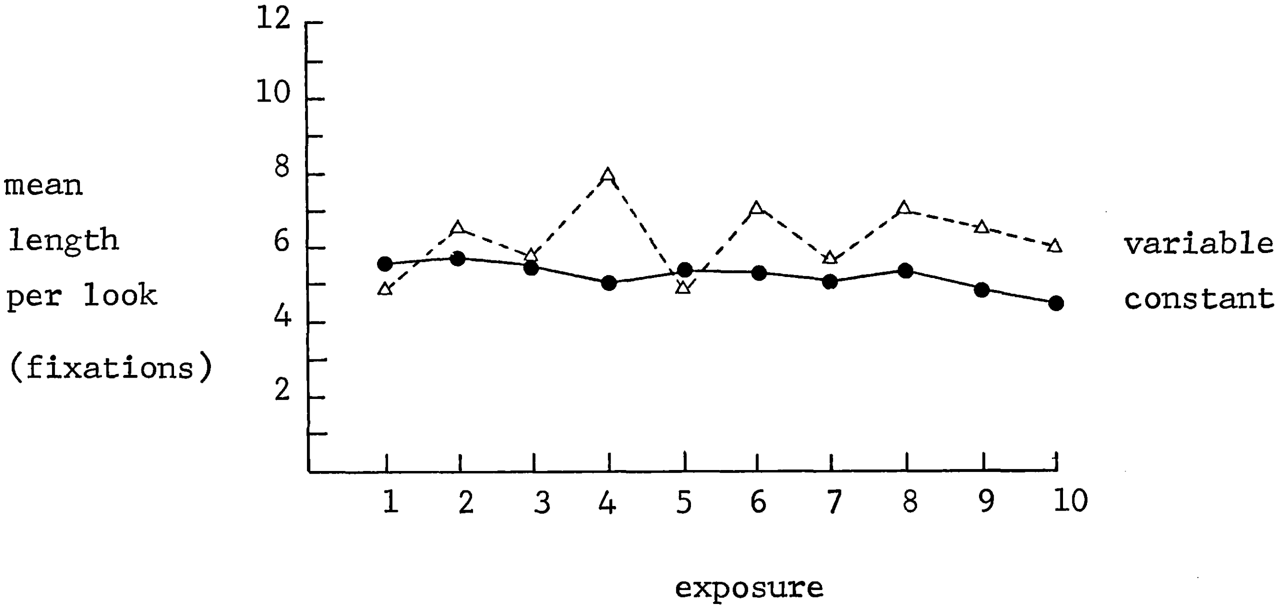


a) Initial memory blank

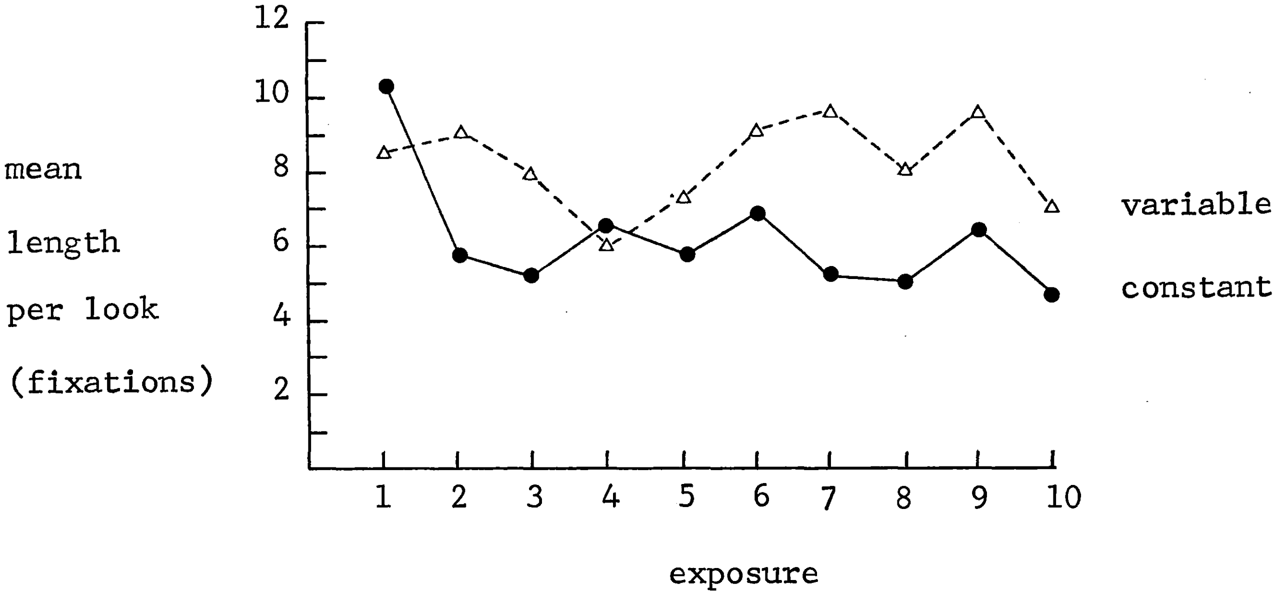


b) Initial memory primed

Fig. 57. Total amount of looking at patterns across 10 exposures.

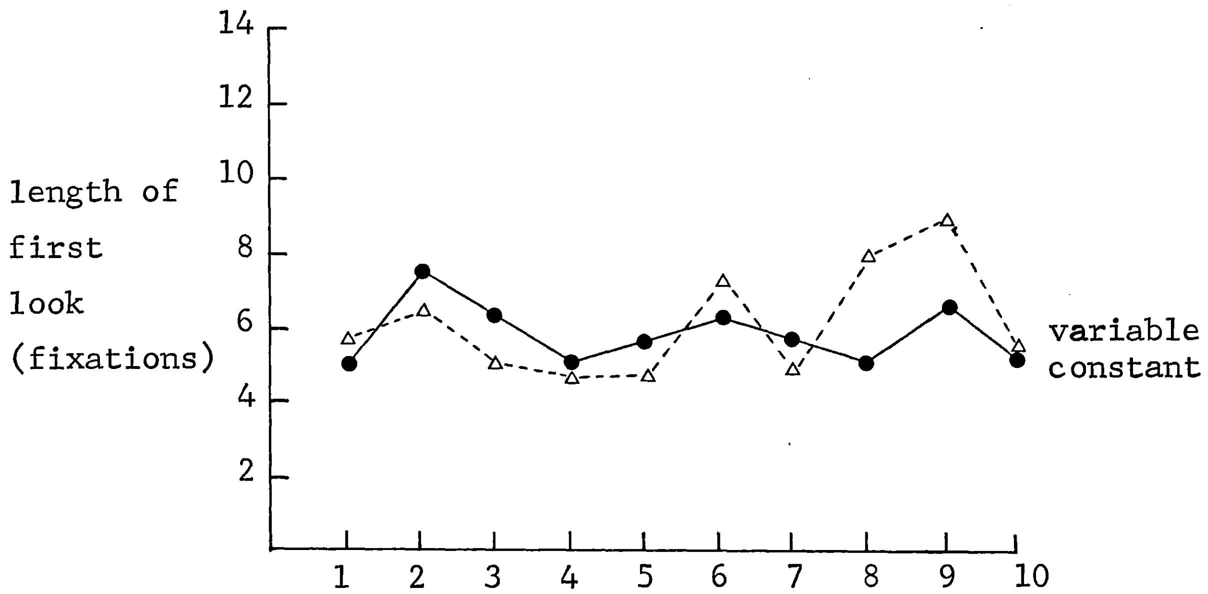


a) Initial memory blank

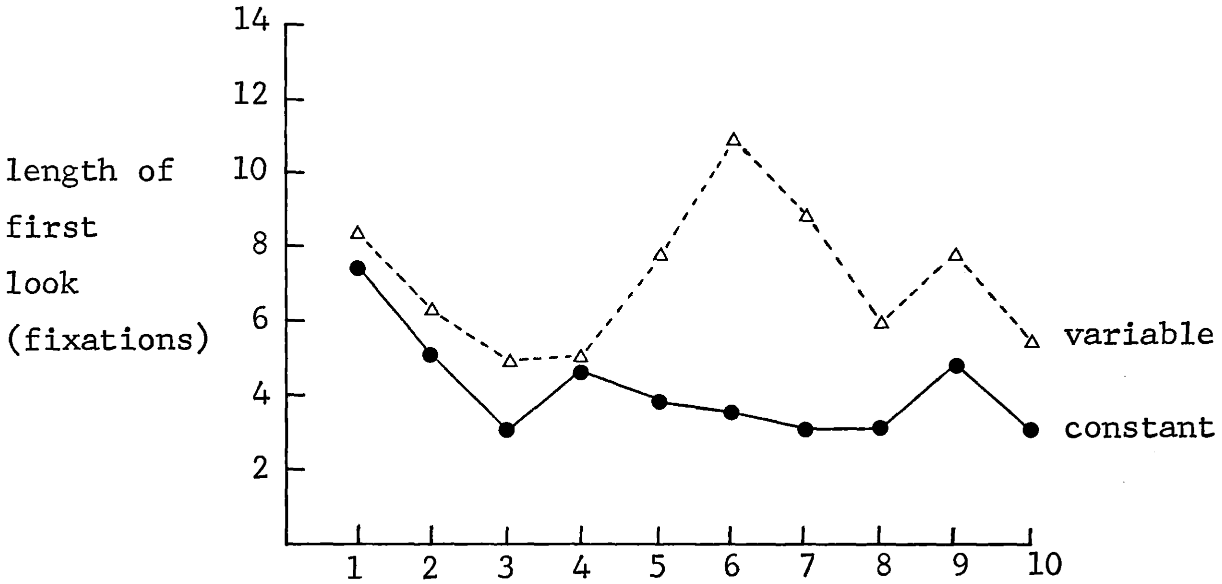


b) Initial memory primed

Fig. 58. Mean length of each look at patterns across 10 exposures.



a) Initial memory blank



b) Initial memory primed

Fig. 59. Length of first look at patterns across 10 exposures.

measures the blank memory condition produced curves which are close together, while the primed memory has them further apart with the variable patterns commanding longer looks.

Discussion.

These simulated results are in fairly good agreement with those obtained by Fantz, and CYCLOPS also requires some degree of visual experience before it is able to demonstrate pattern recognition by means of attentional preferences. Although the percentage scores in figure 56a do not exactly match those obtained by Fantz, it is still clear that the primed memory caused CYCLOPS to look relatively less at the constant pattern. The results achieved with other measures are also in agreement and show the effects clearer, and it is unfortunate that Fantz did not report them in his papers.

The explanation of this developmental effect resides with the discrepancy principle, In both conditions of blank and primed memory CYCLOPS was able to learn and recognize the constant pattern. When this was achieved there was no discrepancy and the constant received short looks. This meant that to show a preference for the variable patterns, they would have had to receive long looks. This could only have been achieved if the fixation sequences on variable patterns were moderately discrepant with the contents of memory, but this was impossible when the memory was blank. Only the primed memory permitted the moderate discrepancy to occur and the variable patterns were looked at longer. It is interesting that this was also the reason for the tendency for CYCLOPS to look more at the variable patterns towards the end of the blank memory exposures. By this stage several patterns had been scanned and a number of entries made in memory, and these were sufficient to produce moderately discrepant sequences of fixations with the variable patterns of the final exposures.

In conclusion it may be stated that CYCLOPS is able to recognize patterns by looking less at one which has been repeatedly exposed than at a pattern which is new. This effect is not shown immediately, but must develop and requires that CYCLOPS has had experience of looking at a number of patterns. This behaviour resembles that of the infants in the Fantz experiment.

3. Simulation of the experiment by Caron and Caron (1969).

a) The infant study.

Design.

The aim of this experiment was to investigate the effects on infants' looking of the repeated exposure of a stimulus. In addition, the influence on looking of the level of complexity of the stimulus was studied. This latter aspect was not included in the simulation because

CYCLOPS is not designed to respond to complexity. In any case, stimulus complexity is an obscure dimension in infant studies, and results have generally only been obtained with a very limited range of stimuli (chequerboards varying in the number of component squares are typically used). Although significant effects have been shown, it would seem these are only applicable to chequerboards, and the usefulness of the complexity dimension may be questioned.

The experiment (which repeated an earlier study by Caron and Caron, 1968) involved 15 successive exposures of single stimuli for 20 seconds. In each of the first 4 exposures a new stimulus was used, these consisting of irregular shapes or arrangements of dots and lines. On exposure 5 the test stimulus (a chequerboard) was shown, and this stimulus was repeated for exposures 6 to 9. On exposure 10 the test stimulus was removed and a new one shown, and further new stimuli were used in exposures 11 and 12. For exposure 13 the test stimulus was presented once more, but the experiment concluded with presentations of new stimuli for exposures 14 and 15. The sequence of presentations was therefore - exposures 1-5, a new stimulus, exposures 6-9, a repetition of stimulus 5, exposures 10-12, new stimuli, exposure 13, stimulus 5, and exposures 14-15, new stimuli.

A concealed observer looked at the reflection of the stimulus in the infant's cornea and from this judged whether the stimulus was fixated or not. The duration of each look at the stimulus and the number of looks were recorded for each exposure. A total of 96 infants were used, one half boys and the other girls with ages from 14 to 16 weeks.

Results.

The total amount of looking at the stimuli is shown in figure 60. This data is derived from the results reported by Caron and Caron (1969), and each score is the mean for all subjects. The curve reveals a high level of looking at the varying stimuli of the first 5 exposures, but there was a steady and significant decline in looking at the repeated test stimulus in exposures 6 to 9. This contrasted with a significant increase in looking from exposure 9 to 10, and the looking was maintained at a high level for exposures 10 to 12. There was a significant drop across exposures 12 to 13 when the test stimulus was shown again, and a significant increase when a new stimulus was shown in exposure 14.

These results indicate that infants look less at stimuli which are repeatedly exposed, and provides evidence that this is due to recognition since the amount of looking recovered when a new stimulus was seen. The memory of the test stimulus was retained over a period of time since

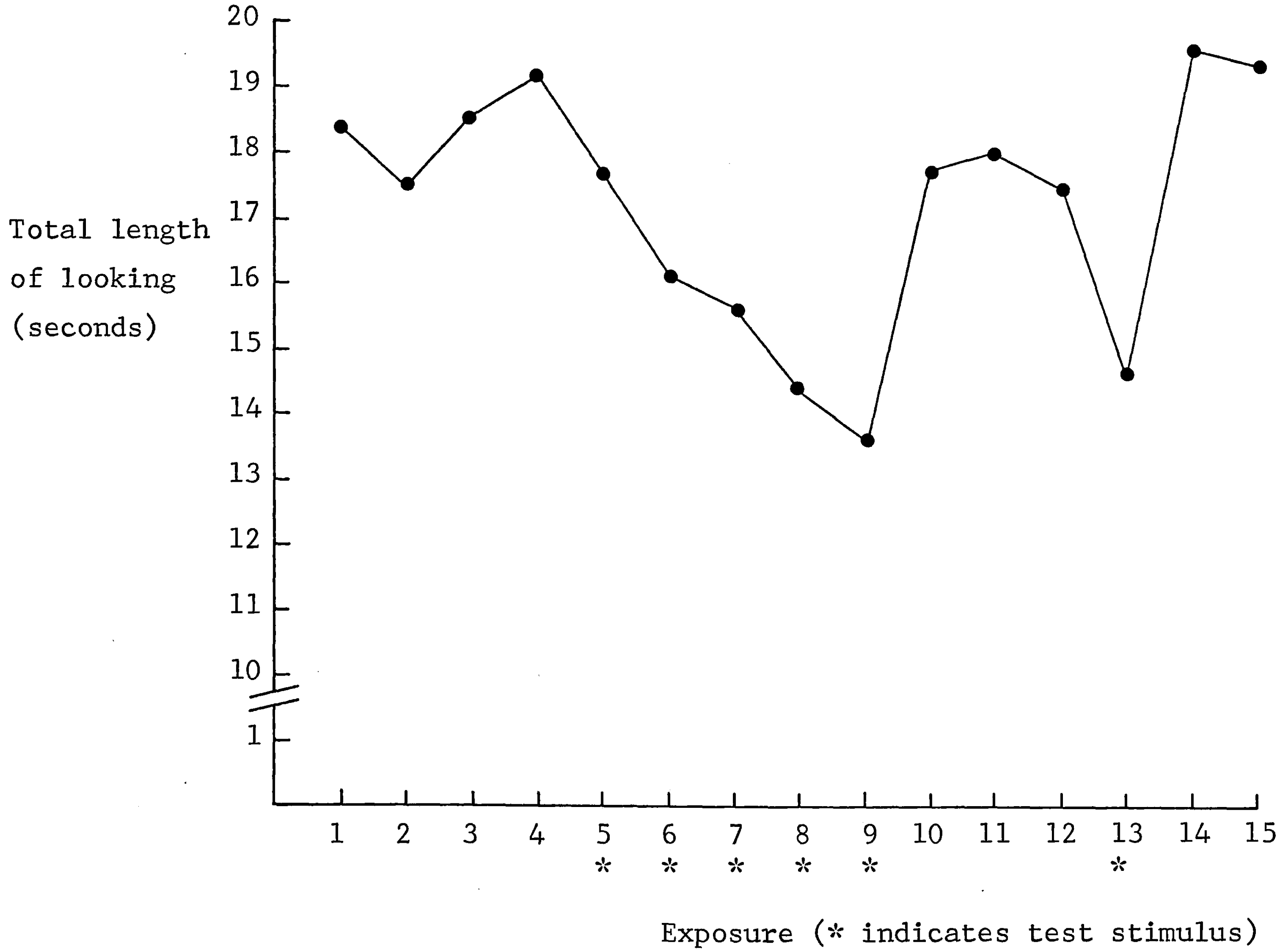


Fig. 60. Mean total length of looking at stimuli in 15 exposures by 96 infants (derived from Caron & Caron 1969)

the decrease in looking was still shown in exposure 13 which followed an interval of 60 seconds after the previous exposure of the same stimulus.

b) The simulation with CYCLOPS.

Design

In order to simulate the level of visual experience attained by the 3½ month old infants, each experimental session was begun with CYCLOPS having a primed memory. This memory was identical to the one used with the Fantz simulation. 10 patterns were used in the experiment, and these are illustrated in figure 55 (except for the pattern indicated by " which was not included). One pattern was selected as the test pattern, and this was shown during exposures 5 to 9 and exposure 13. When patterns were exposed to CYCLOPS they were located in the centre of the visual world, and the length of an exposure permitted CYCLOPS to make 30 fixations anywhere in the visual world. During the first 4 exposures the patterns were selected randomly, a new one being shown with each exposure. This was followed at exposure 5 by the test pattern which was retained until the end of exposure 9. Randomly chosen patterns were again shown during exposures 10 to 12 (though once a pattern had been exposed it was not shown again during the same session). At exposure 13 the test pattern was shown once more, and finally the two remaining patterns yet to be used were shown in exposures 14 and 15.

A total of five separate sessions were conducted in this manner using the same set of 10 patterns but with randomly determined exposures of the varying patterns and 5 different test patterns. The scores which are presented in the results section are therefore the means of 5 individual scores.

One addition was made to the Caron and Caron design by the inclusion of 5 control sessions. Instead of repeating the test pattern during exposures 6 to 9 and 13, new patterns were shown (see figure 61). The results with these controls serve to show how CYCLOPS behaved when a pattern was not repeatedly exposed. 5 control sessions were conducted with the order of presentation of the extra control patterns randomly determined.

Results.

The total amount of looking which the patterns received during each exposure is shown for the experimental and control groups in figure 62. These results should be compared with those obtained with infants in figure 60. There is a fairly close agreement between the infant and simulation curves, though the decline in looking at the test patterns was not so striking with the simulation. This would appear to be partly due to the rather low level of looking at the patterns of the first 5 exposures (a mean

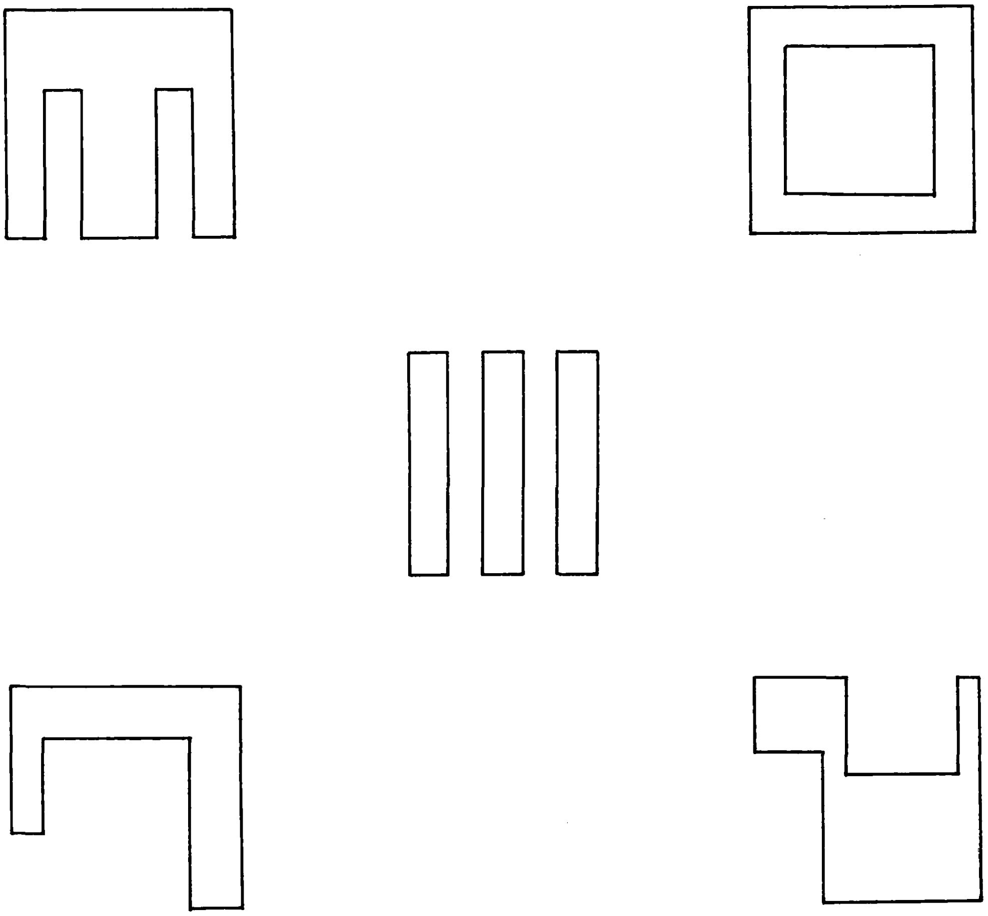


Fig. 61. The 5 patterns used in the control sessions of the Caron & Caron simulation.

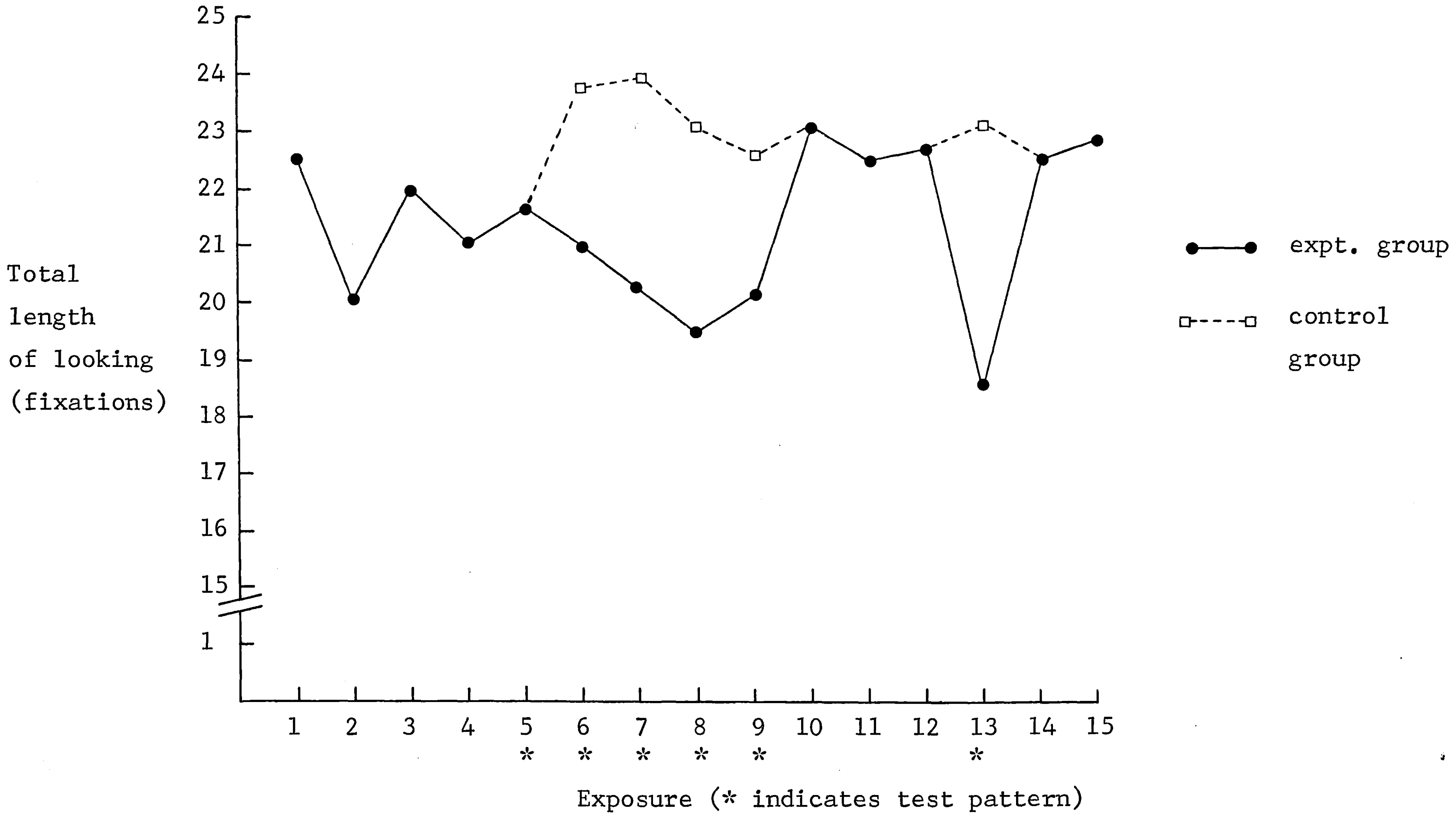


Fig. 62. Total length of looking at patterns in 15 exposures by CYCLOPS.

of 21.5 fixations as opposed to a mean of 22.7 fixations for exposures 10, 11, 12, 14, and 15). However, there was a gradual decline in looking at the test pattern, and a sharp increase when a new pattern was shown at exposure 10. The decline is most noticeable when compared with the results for the control group where looking was maintained at a high level. The two curves for exposures 10 to 15 are very similar for both infants and CYCLOPS, and the simulation produced a sharp drop in the amount of looking in exposure 13 (the repeat of the test pattern).

These effects can be seen when the other measures of looking are used, and figure 63 shows this for the mean length of each look, while figure 64 shows the curves for the length of the first look. Neither of these measures was reported by Caron and Caron which is unfortunate as the curve for the length of the first look shows the decline with the test pattern most clearly. Schaffer and Parry (1969) conducted a similar experiment with 6 month old infants, and the curve they report for the length of the first look is very similar to the one obtained with CYCLOPS.

Discussion.

In this experiment CYCLOPS again was able to recognize patterns even though the design was very different from the Fantz study (single presentations as opposed to pairs of patterns). The test pattern which was repeatedly exposed

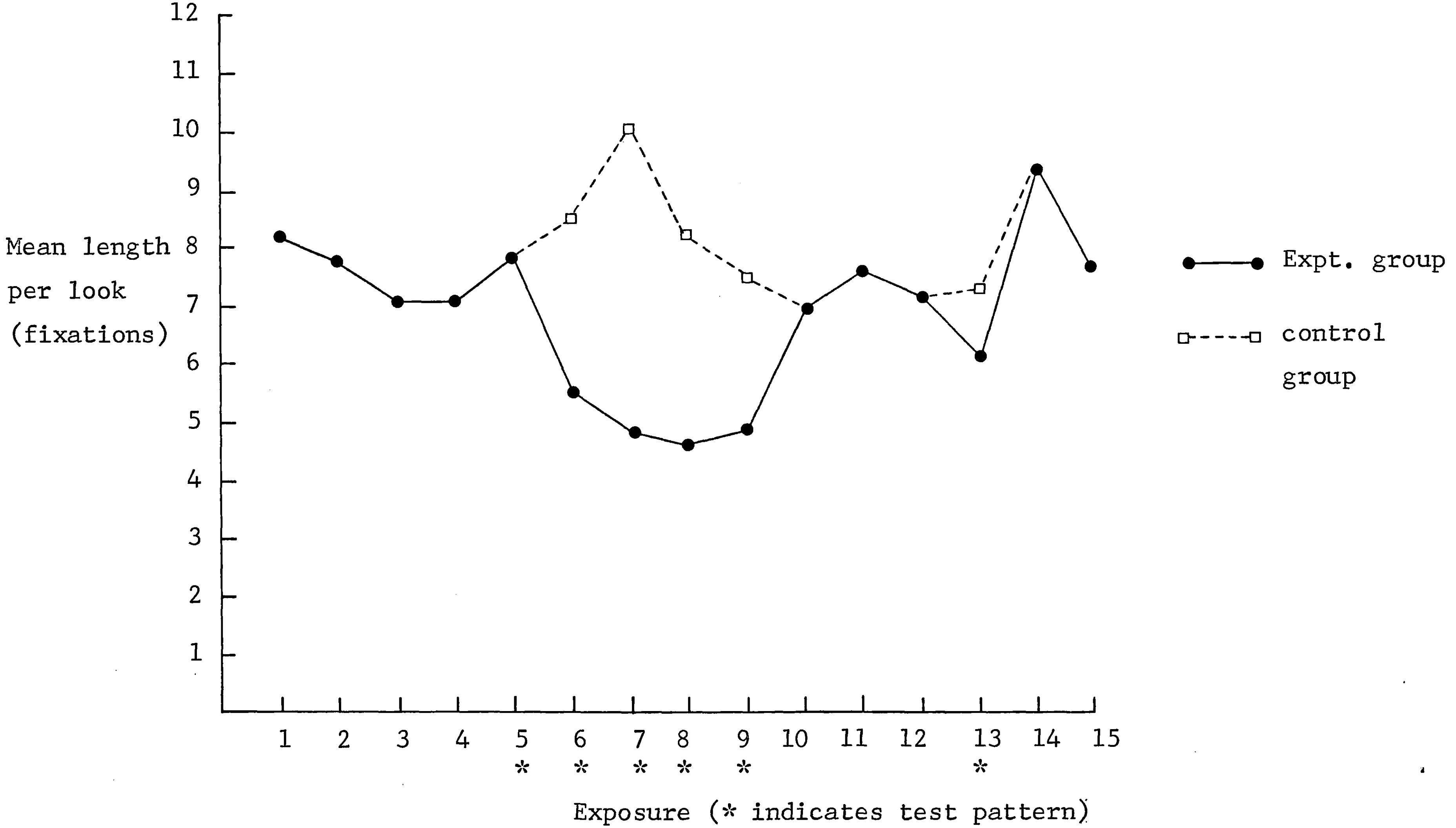


Fig. 63. Mean length per look at patterns in 15 exposures by CYCLOPS.

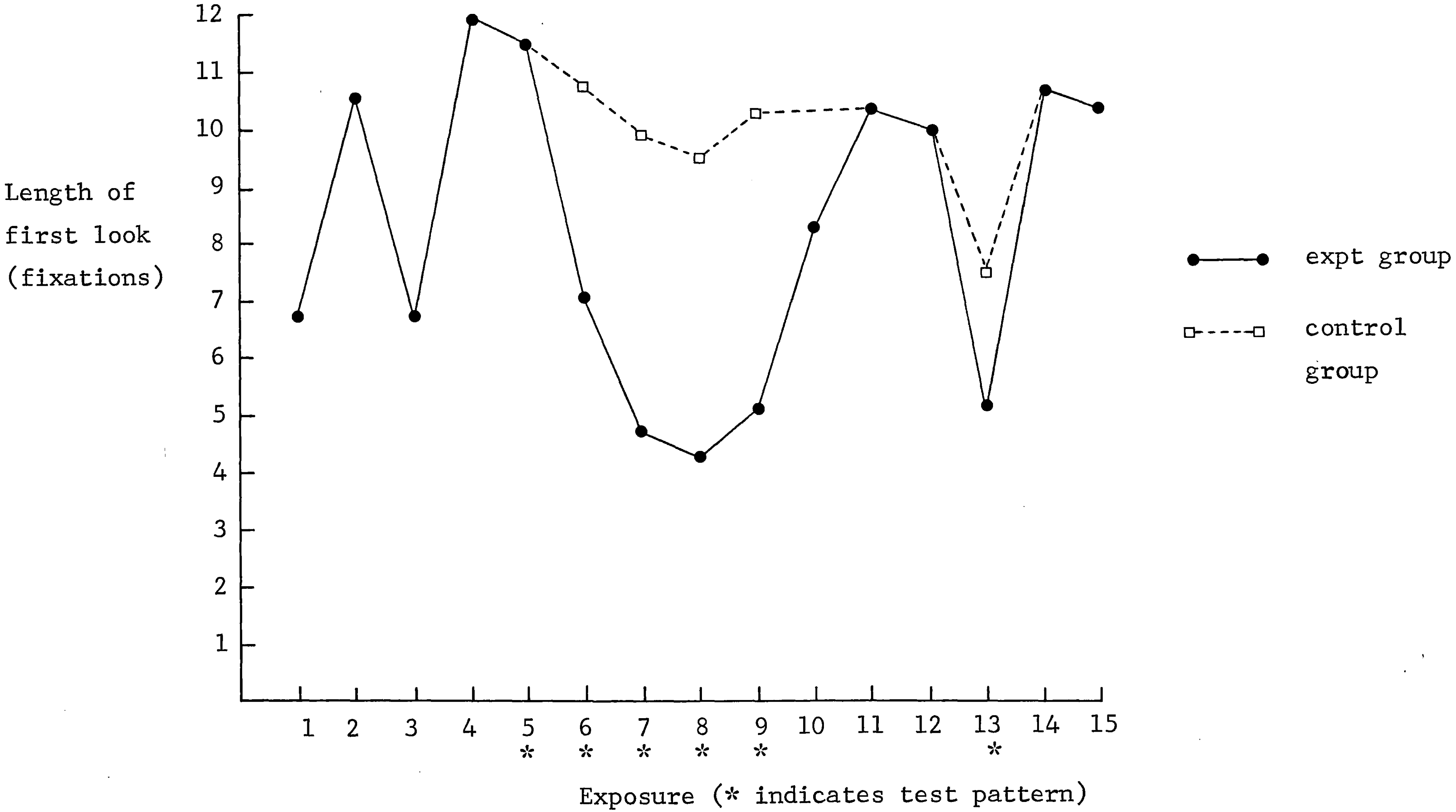


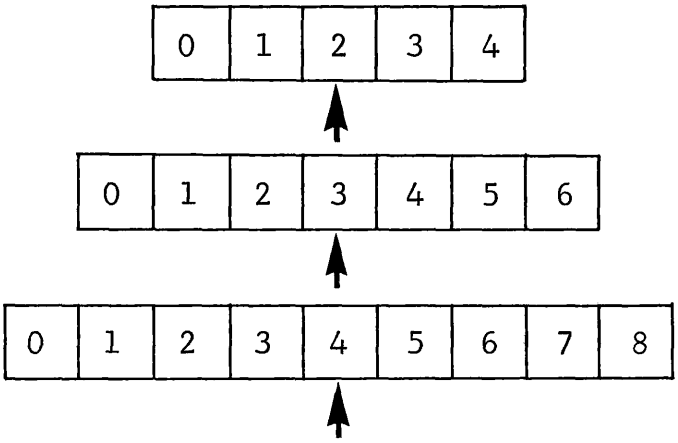
Fig. 64. Length of first look at patterns in 15 exposures by CYCLOPS

received shorter looks, and this level of looking was maintained even after a delay (exposure 13). This was due to the discrepancy principle, and as matching predictions were acquired for the test pattern, fixation sequences ceased to be discrepant and became shorter.

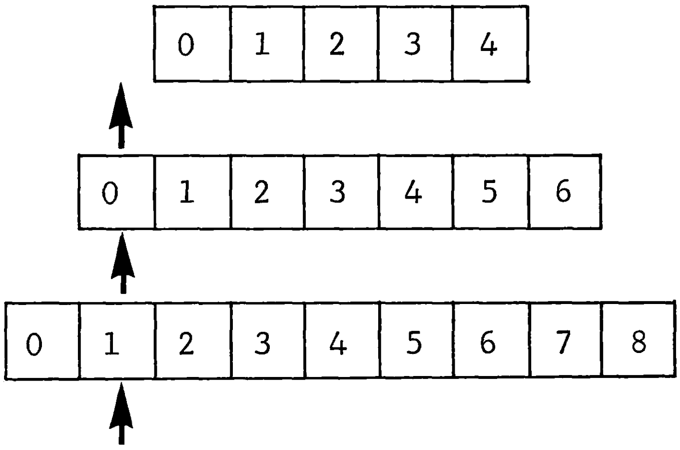
c) A digression: The effects on looking of altering the length of the discrepancy index.

In all the experiments reported, CYCLOPS has operated with a discrepancy index having a separation of 5 spaces between its upper and lower limits. This setting is arbitrary, and it is pertinent to ask whether altering this separation affects looking behaviour in any way. If the two ends of the index are close together, it would be expected that the lengths of looks at patterns will be shortened. Conversely, if the two ends are far apart, looks will become longer.

The resoning behaind this is shown in figure 65. In 65a, there are three indices with limits of 0-4, 0-6 and 0-8 respectively. Each has a pointer on the central location (either at 2, 3 or 4). If a series of 3 matching predictions occurs, the pointers will be moved 3 spaces towards the lower end at the left. The outcome for each index is shown in 65b. and it can be seen that with the shortest index the pointer has moved beyond the lower end and the fixation sequence will be terminated by a blind move. For the



a) 3 discrepancy indices; short, medium and long. The pointers are located initially in central positions.



b) Following a series of 3 matching predictions, the pointers are moved 3 spaces left towards the lower end. For the short index the pointer has gone beyond the end and the fixation sequence is terminated by a blind move. With the other indices, the fixation sequence will continue.

Fig. 65. The relationship between size of discrepancy index and the length of fixation sequences.

remaining two indices the pointer has not gone beyond the end and the fixation sequence will continue. If another matching prediction occurs, there will be a further movement of the pointers to the left, and this time it will go beyond the end of the middle index, but will still be within the limits of the longest index. While the fixation sequence will now be terminated for the middle index, it may continue for the longest index. Clearly, the greater the separation, the longer the sequences of fixations will last before ending with a blind move.

The separation between the ends of the discrepancy index would also have an effect on the number of looks CYCLOPS takes at a pattern. The shorter the length of each look, the more chances there are for taking further looks. If each lasted for 4 fixations, a maximum of 7 looks could be made during a period of 30 fixations. On the other hand, if each look lasted for 10 fixations, only 3 looks could be taken during the same period.

In order to examine these predicted effects, the Caron and Caron simulation was repeated twice. For one repetition the separation between the ends of the discrepancy index was 3 units, and this will be referred to as the 'short' version. The other repetition had a separation of 7 units, and this will be called the 'long' version. The simulation reported above used a separation of 5 units and will be called the 'medium' version. These two further simulations only consisted of the experimental sessions in which the test stimulus was repeatedly exposed. The control sessions were not repeated. A total of 5 sessions were run for both the short and long versions of CYCLOPS.

The curves which the three types of index produced for the total amount of looking are shown in figure 66. As was predicted, the long index produced most looking at the patterns and the short index produced the least. The medium index produced a level of looking intermediate between these two for all exposures except 2 and 10. The decline in looking at the repeated pattern in exposures 5 to 9 and 13 is shown by the short index version, but the long index version only produced a clear decrease at exposure 13.

The curves for the mean length of each look are shown in figure 67. Again there is an orderly relationship between the mean length per look and the separation between the ends of the discrepancy index. The decline in the mean length of each look with the repeated patterns is most noticeable for the long index version, and this contrasts with the results for the total amount of looking. The short index version, on the other hand, shows the smallest decline in the mean length per look for the repeated patterns.

The same ordering of results is revealed in figure 68

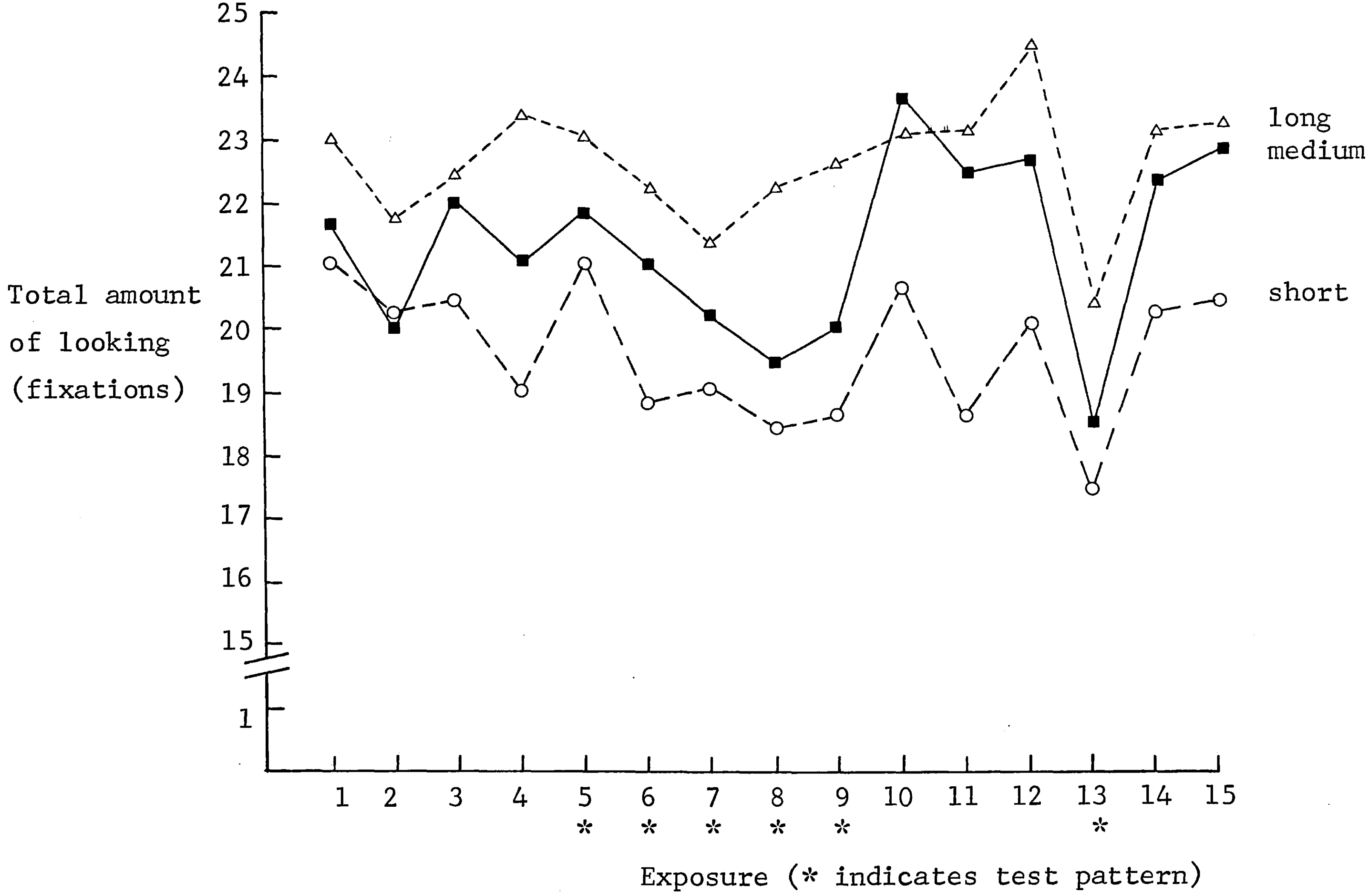


Fig. 66. Total amount of looking at patterns and length of discrepancy index used by CYCLOPS

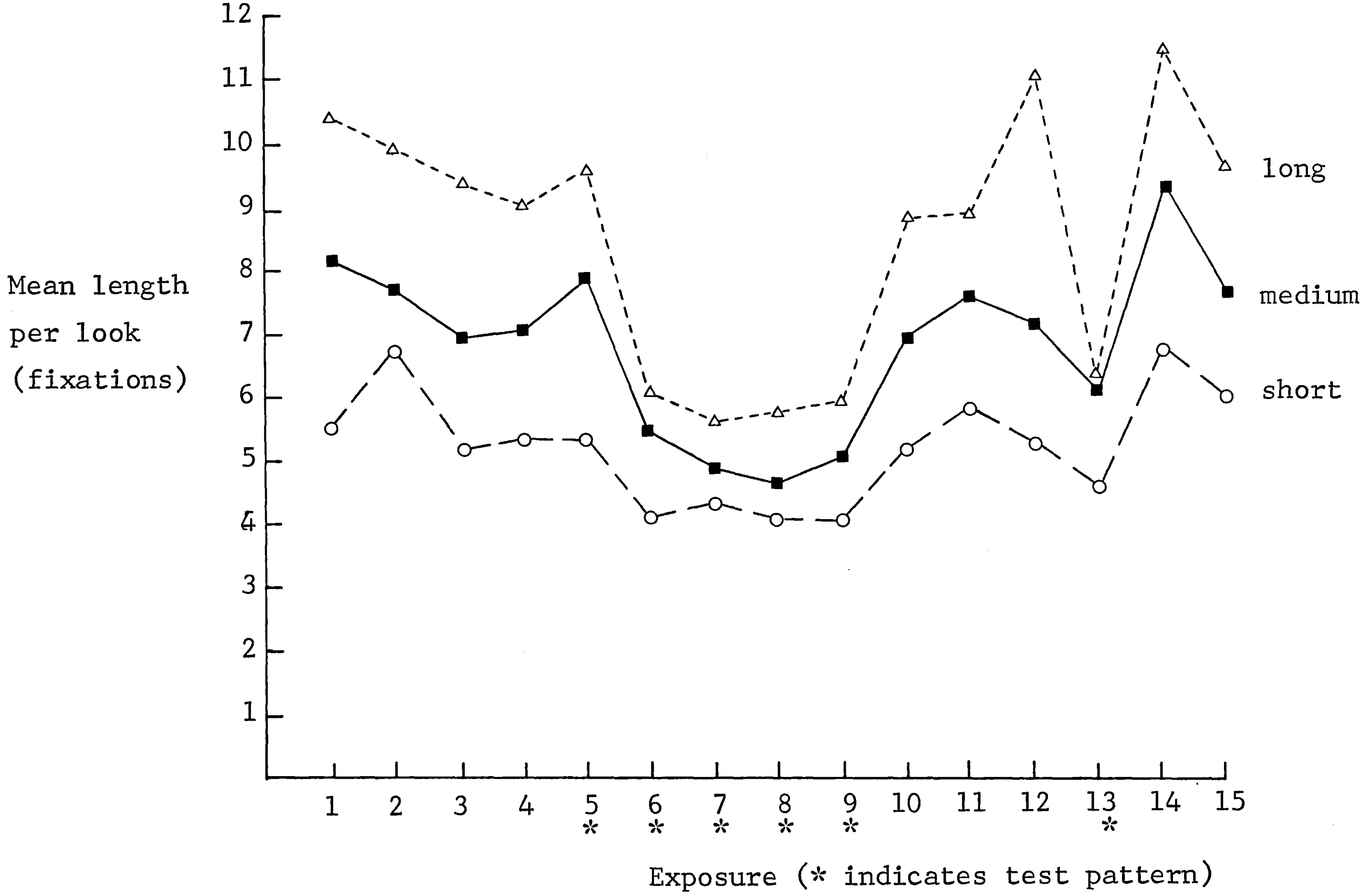


Fig. 67. Mean length per look at patterns and length of discrepancy index used by CYCLOPS

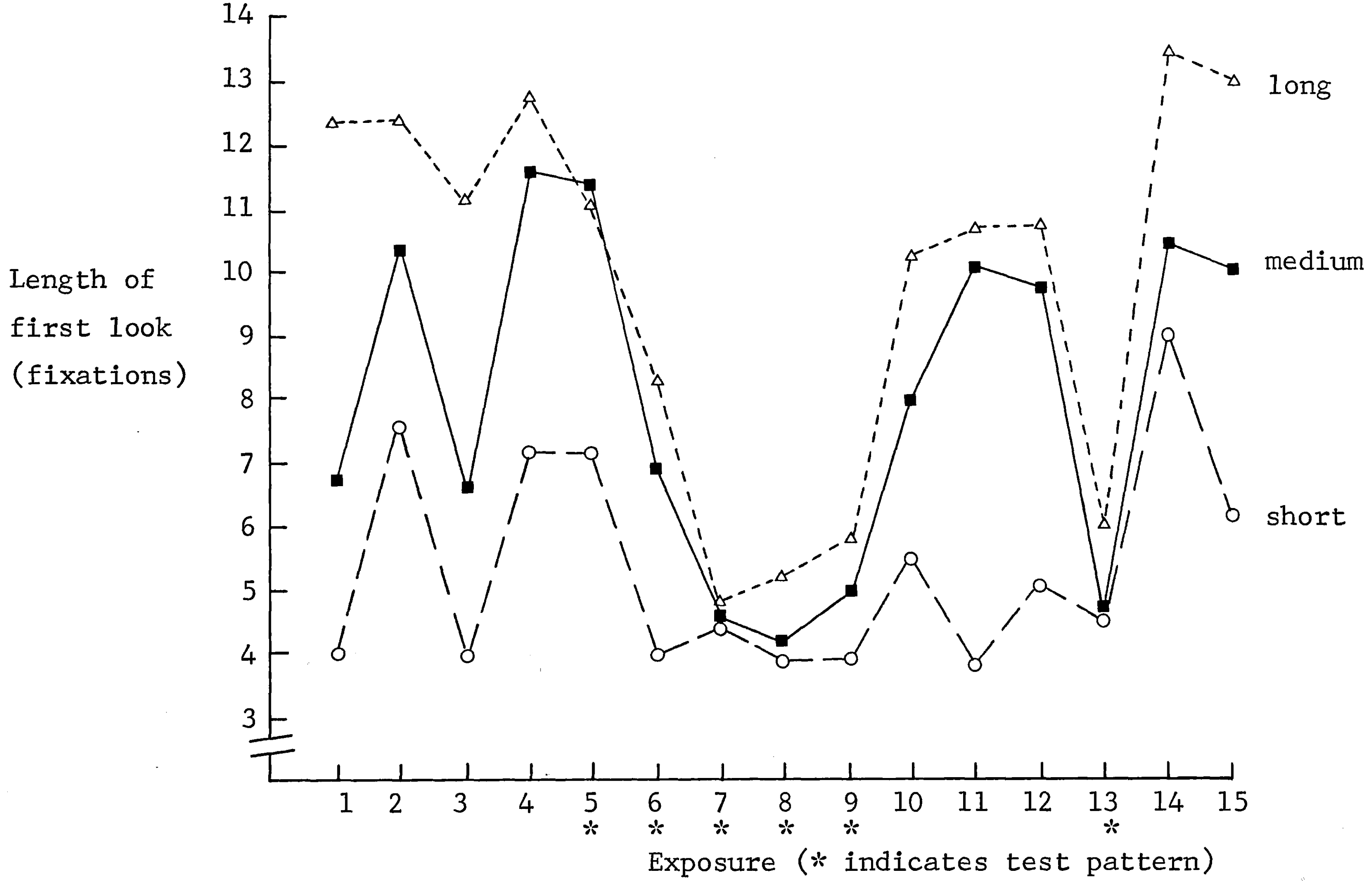


Fig. 68. Length of first look at patterns and length of discrepancy index used by CYCLOPS.

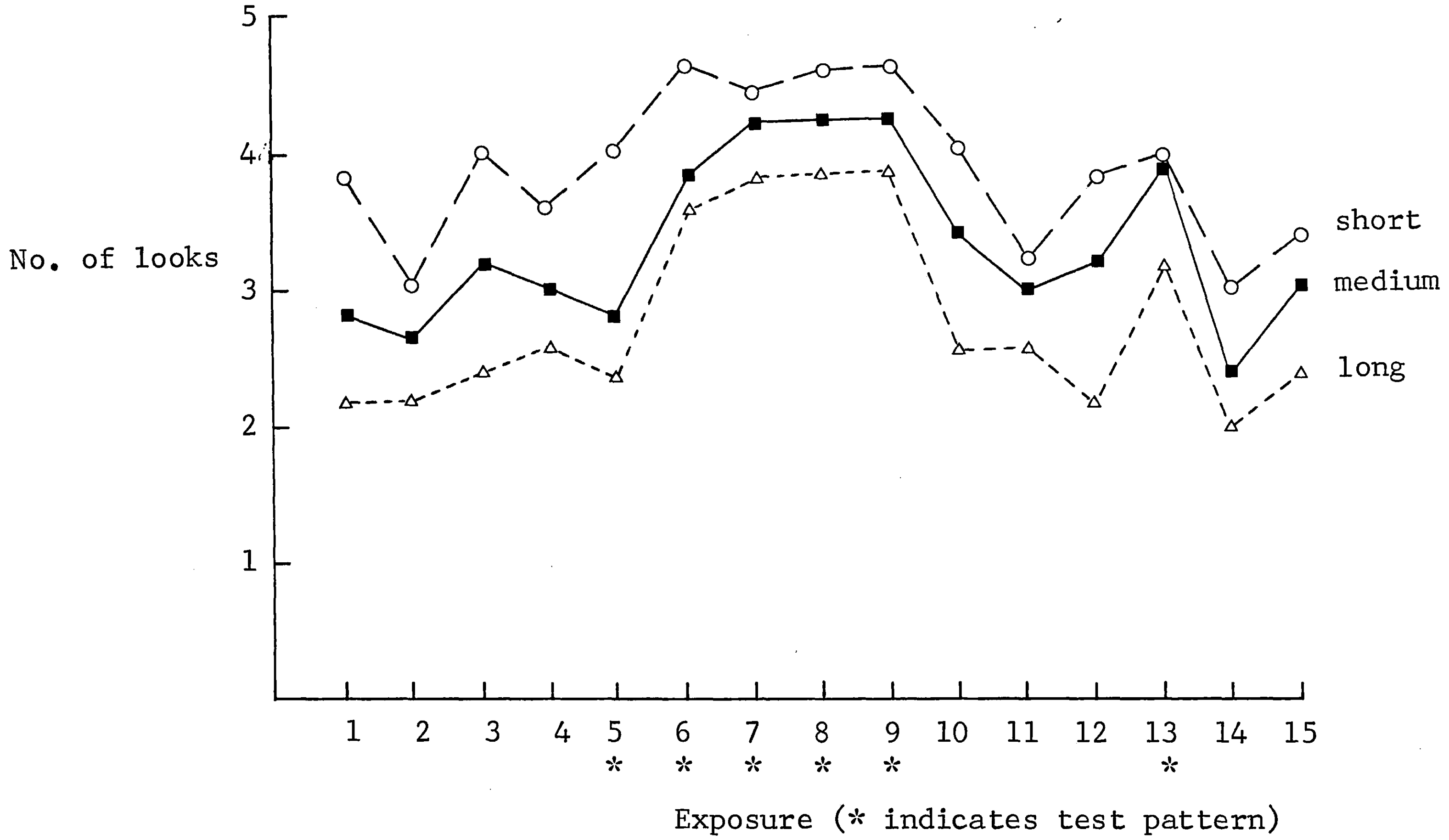


Fig. 69. Number of looks taken at patterns and length of discrepancy index used by CYCLOPS.

for the length of the first look at the patterns. Again it is the long index which produced the longest first looks while the short index produced the shortest and the medium index was intermediate. This measure shows the decline and subsequent recovery of looking most effectively, though again it is difficult to detect the changes for the short index.

In figure 69 the number of looks each index produced is shown. These curves confirm the second prediction; the short index produced most looks at the patterns and the long index produced the least. This measure contrasts with the others as it records an increase for the repeated exposure of the test pattern. This is to be expected with exposures of a fixed length since the decrease in the length of each look is compensated by an increase in their number.

Taken together, these results confirm the predicted effects on looking of variations in the length of the discrepancy index. Although there were some exceptions (eg. the mean length per look for the short index, and the total amount of looking for the long index), the repeated exposure of the test pattern had the same effect with all lengths of index. This means that varying the size of the discrepancy index only affected CYCLOPS' behaviour in a matter of degree. Although the separation of 5 units was arbitrary for the simulations, it need not alter the interpretation of the results.

It is interesting that the results reported in this section resemble the behaviour of children classed as 'reflective' or 'impulsive'. Impulsive children are noted for their speed in solving problems but a capacity for making errors. Reflective children are slow and methodical but more accurate (Kagan, 1966). Studies of the eye movements of these children while solving picture matching tasks show that the impulsive child makes fewer fixations than the reflective (Zelniker et al., 1~~0~~972, Drake, 1970). If a version of CYCLOPS with a short discrepancy index is classed as impulsive while a version with a long discrepancy index is reflective, these findings correspond with the results shown in figure 69.

Further support for this relation comes from a number of studies with infants carried out by Kagan (1971). With the young children that were studied (4 to 27 months) the usual tests of impulsivity/reflectivity could not be conducted, but Kagan was able to detect a similar dimension which he termed 'conceptual tempo'. Some evidence was produced which suggested a relationship between a child's tempo rating for visual and motor behaviour. With this dimension, fast tempo corresponds to impulsivity and slow tempo to reflectivity. A fast tempo child was quick to answer when searching for an embedded figure (ie. looked less), but mistakes were often made. When presented with a number of toys, such a child investigated them all repeatedly but with only short periods for each. In addition, fast tempo children only looked for short periods at models of faces when 13 months of age, and the mean length of each look was small.

Slow tempo children showed the reverse effects; they took longer to find an embedded figure but were more often correct, they played with fewer toys and for longer periods with each, and they looked longer at the faces. Kagan managed to detect these effects with infants as young as 4 and 8 months and discovered that children classified as fast tempo at the age of 27 months had looks of short duration at visual stimuli presented when they were only 4 and 8 months of age. Children later classified as slow tempo took longer looks at the stimuli when they were these ages. Similar differences in the amounts of looking for the short and long index versions of CYCLOPS are shown in figures 66 to 68.

Although these findings are tentative and require further study, there would seem to be some evidence for the existence of conceptual tempo. The significance of this for CYCLOPS is that the simple adjustment of a parameter (the length of the discrepancy index) produced the kind of looking behaviour shown by fast, slow and medium tempo children and infants. The implication of this for a theory of development is that it is not necessary to complicate the theory with an extra process as the explanation of tempo may be achieved by reference to the discrepancy principle.

4. Simulation of the experiment by Fagan (1971).

a) The infant study.

Design.

This experiment was intended to examine the ability of infants with ages of 15 to 33 weeks to recognize stimuli over a period of time. The basic strategy involved the initial exposure of a stimulus for a period during which it became familiar to the infants. Recognition of this stimulus was tested by exposing it paired with a new stimulus and recording the amount of looking at each member of the pair. If the initial stimulus was recognized it would be looked at less than the one which was new. This recognition test resembled the design used by FANTZ (1964). Tests of recognition were conducted twice; immediately after familiarization and following a delay of several minutes. A comparison of these two recognition tests would indicate whether the infants were able to retain a memory of the familiarized stimulus during the delay.

For the familiarization exposures the infants were shown a p~~e~~air of identical patterns for 2 minutes. Corneal reflections of the stimuli indicated to a hidden observer which stimulus was fixated, and the total amount of looking that each received was recorded. Since this was a pair of identical stimuli, it was not expected that one would be looked at more than the other. The familiarization was immediately followed by 2 recognition exposures lasting only 10 seconds each. For both of these exposures the familiarized stimulus was paired with a new stimulus, the positions of the two being reversed in the second recognition exposure. The amount of looking each stimulus received was again recorded for these 10 second exposures.

Following the second recognition exposure there was an interval of 30 seconds during which nothing was shown to the infants. When this period was finished, a second set of familiarization and immediate recognition exposures using different stimuli were conducted. These were again followed by a 30 second interval and then a third and final set of familiarization and immediate recognition exposures. Another 30 second period was allowed to lapse, and this was followed by the tests for delayed recognition. These were an exact repetition of the immediate recognition exposures but without the intervening familiarization exposures or 30 second intervals. This design is summarized in figure 70 which shows the structure of an experimental session.

seconds	stimuli		exposure
120	A	A	familiarization 1
10	A	B	immediate recognition 1
10	C	A	
30			interval
120	D	D	familiarization 2
10	D	E	immediate recognition 2
10	F	D	
30			interval
120	G	G	familiarization 3
10	G	H	immediate recognition 3
10	I	G	
30			interval
10	A	B	delayed recognition 1
10	C	A	
10	D	E	delayed recognition 2
10	F	D	
10	G	H	delayed recognition 3
10	I	G	

Fig. 70. Design of the experiment by Fagan (1971). 9 stimuli were used, indicated by letters A to I.

The delay arises because of the intervening exposures between the familiarization exposure of a stimulus and the final delayed recognition exposure. However, there would be considerable differences in the size of this delay depending on the serial position of the familiarization exposures. For the first familiarized stimulus, the delay was 390 seconds, while for the second stimulus it was 233 seconds and for the third it was only 90 seconds. It is possibly for this reason that Fagan varied the serial order of the delayed recognition exposures, using the three orthogonal orderings of 1-2-3, 2-3-1, and 3-1-2. This did not have a great effect on the size of the delays since their mean values were 410, 233, and 70 seconds for the stimuli presented first, second and third respectively.

The experiment was conducted with 72 infants, each receiving exactly the same stimuli in the familiarization and recognition exposures, though in different orders.

Results.

Fagan reported his results in terms of the mean percentage of the total looking time spent fixating the new stimuli of the recognition exposures. These results are shown in figure 71 and the bar diagrams were derived from the published data. For each of the three immediate recognition exposures the new stimuli were looked at significantly more of the time that the familiar ones. They

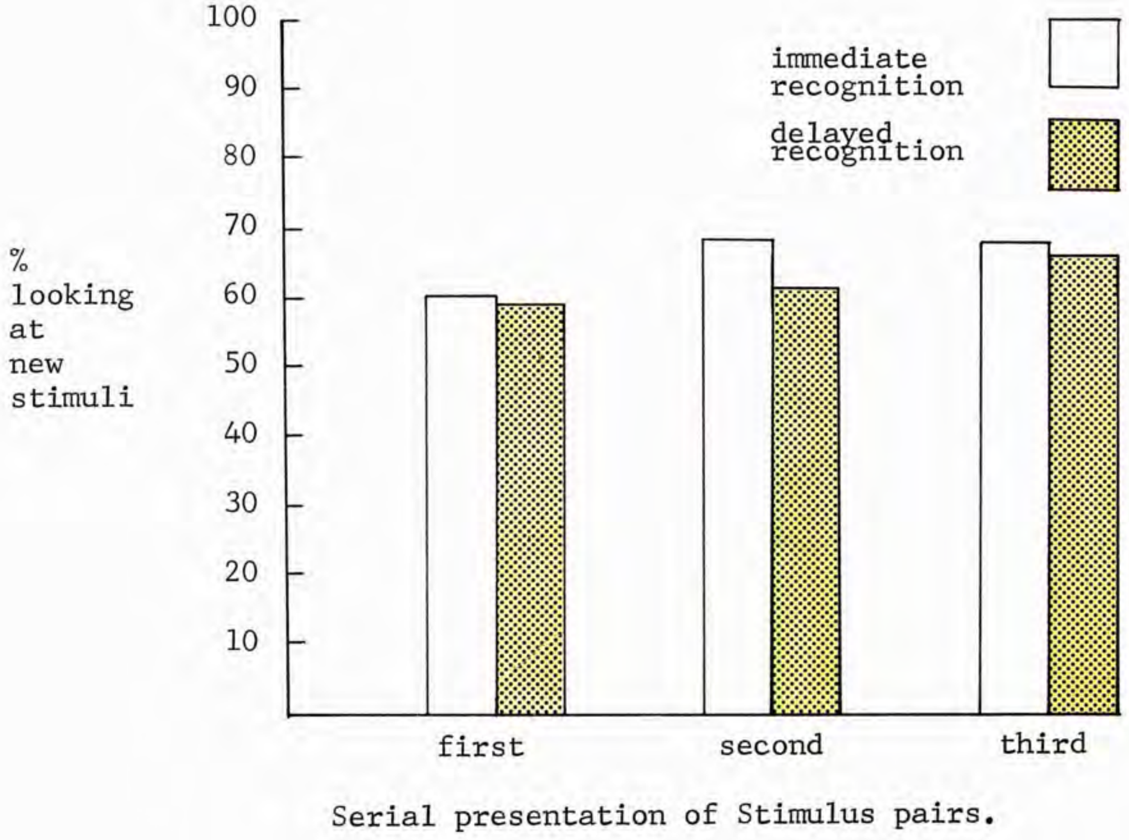


Fig. 71. Percentage looking at new stimuli by infants during immediate and delayed recognition exposures (derived from Fagan, 1971).

amount of looking the new stimuli received varied from 60% to 69% of the total. Following the delay, the amount of looking at the new patterns altered very little, varying from 60% to 68% of the total. There were no significant differences between the means for the order of presentation, and there were no significant differences between the immediate and delayed recognition scores.

These results indicate that the infants retained a memory of the familiarized stimuli for periods ranging from about 1 to 7 minutes, and their distribution of looking at the familiar and new stimuli was unaffected by this delay.

b) The simulation with CYCLOPS.

Design.

CYCLOPS began each experimental session with a primed memory which was the same as the memories used in the previous two simulations. Fagan used infants of 15 weeks or more, so CYCLOPS was allowed to begin the experiment with a history of visual experience. The structure of each experimental session was as follows. A pair of identical patterns was presented during the first familiarization exposure. The length of such an exposure permitted CYCLOPS to make 120 fixations anywhere in the visual world. The immediate recognition exposures followed directly and there was no interval. This was un-necessary because an interval would have had no effect on CYCLOPS' behaviour, but would have increased the running time of the program. For each recognition exposure, the familiarized pattern was paired with a pattern which was new for CYCLOPS, and the positions of these patterns were exchanged for the second recognition exposure. These exposures each allowed CYCLOPS to make 15 fixations in the visual world, after which the patterns were removed. The relative lengths of the recognition and familiarization exposures (15:120 fixations) were comparable to the lengths used by Fagan (10:120 seconds).

This procedure was repeated twice using 2 different patterns in the familiarization exposures, and 4 new patterns in the further immediate recognition exposures. The series of delayed recognition exposures followed the final immediate recognition exposures and each lasted for 15 fixations. The same pairs of patterns used in the immediate recognition exposures were used for the tests of delayed recognition.

A total of 3 experimental sessions were run, and the same 9 patterns were used in each (these were selected from the patterns shown in figure 55). Each of these 9 patterns was used once in a familiarization exposure, unlike Fagan's experiment in which the same 3 patterns were used with all infants. Because there were only 3 sessions, the same order of presentation of the delayed recognition exposures was used throughout.

Results

The pairs of identical patterns in the familiarization exposures were looked at equally, the mean percentage of the total looking at the left-hand pattern being 52%, 53% and 51% for the 3 sessions. CYCLOPS did not differentiate the patterns which were the same. The results for the immediate and delayed recognition exposures are shown in figure 72. CYCLOPS looked more at the new patterns during the immediate recognition exposures, the mean percentage of the total looking time varying from 55% to 75%. If these results are compared with those reported by Fagan (figure 71), it can be seen that for the first and second immediate recognition exposures CYCLOPS looked slightly more at the new patterns than the infants, but for the third exposure CYCLOPS looked less.

In the delayed recognition exposures, CYCLOPS still looked more at the new patterns. The amount of looking varied from 59% to 69% of the total. There was a small decrease from the immediate to delayed recognition exposures, but it was not great and the overall mean for looking at the new patterns was 66% of the total for immediate recognition, and 64% for delayed. CYCLOPS looked slightly more at the new patterns during delayed recognition than did the infants.

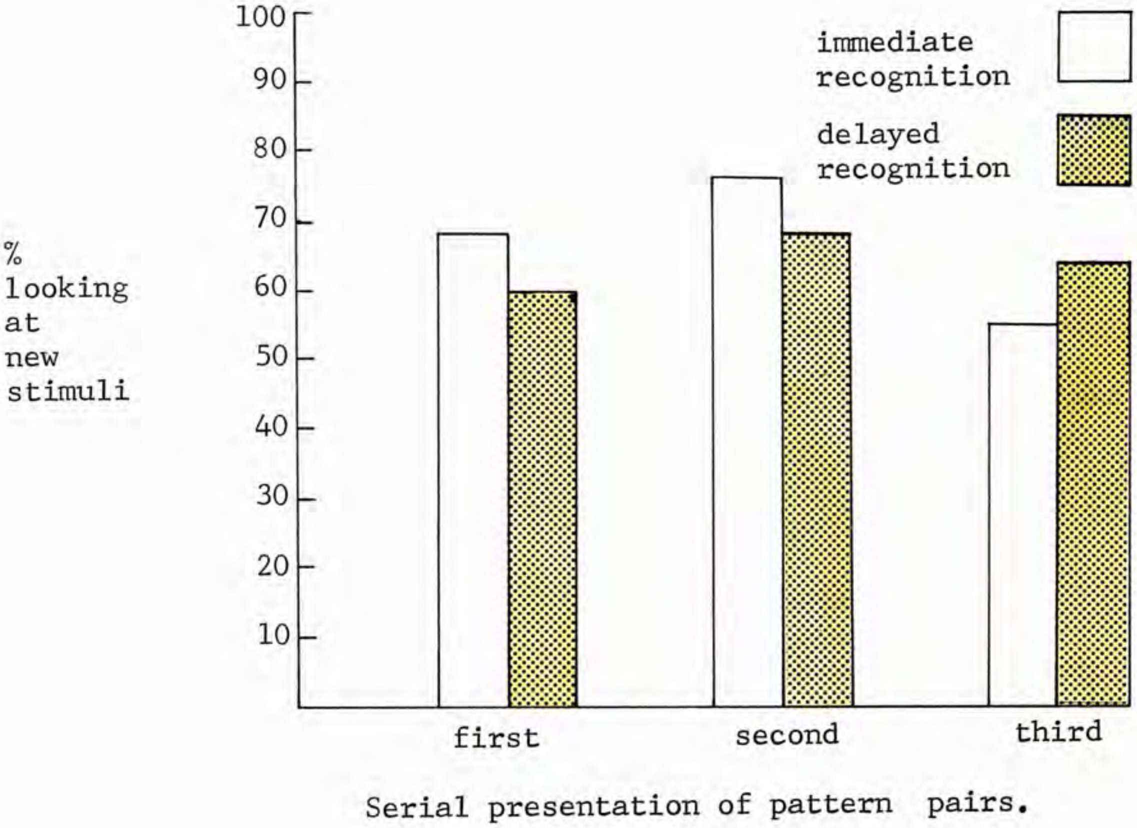


Fig. 72. Percentage looking at new patterns by CYCLOPS during immediate and delayed recognition exposures.

Discussion.

The results of this third simulation again show that CYCLOPS behaved in a manner resembling infants. CYCLOPS was able to indicate recognition both immediately after familiarization and after a delay. One contributing factor was the inability of CYCLOPS to forget something once it is entered into memory, though there is some evidence that infants may also have such a robust memory. In a later experiment conducted along the same lines, Fagan (1973) was able to demonstrate recognition after delays of 48 hours and 2 weeks.

A second important factor in these experiments was the short duration of the recognition exposures. If they had been too long, there was a risk that CYCLOPS would have become familiar with the new patterns during the immediate recognition exposures. This would have meant that both types of pattern would have been familiar for the delayed recognition exposure and both would have received equal amounts of looking. A test run with a recognition exposure length of 30 fixations produced such a result, and this suggests that the length of these exposures is critical. It was likely that Fagan used a duration which just allowed him to obtain significant results. However, even though some learning was possible during the immediate recognition exposures, CYCLOPS was still able to look more at the new patterns after the delay.

5. Discussion and conclusions.

One of the problems with computer simulations is the means by which the simulation may be evaluated. A model may be developed, a program written and de-bugged and finally tested by running on a computer, but it is still necessary to determine whether it is capable of modelling the appropriate behaviour. One technique often used is protocol analysis (Newell & Simon, 1972) in which the computer output is compared with the productions of human subjects. A close agreement between the two is taken as an indication that the computer program provides an adequate model of the behaviour. If there are discrepancies, these serve to indicate where the model is deficient and may suggest how the program should be revised.

Although this is now an established procedure, it can often be difficult to carry out if the output from the computer is in a different form from the subject's behaviour. For example, the computer may produce statements involving symbols and the relations between them while a subject provides his answers verbally. This means that a considerable degree of interpretation may be involved in comparing the two sets of outputs, and the danger exists that a wrong interpretation at some point could invalidate the results.

The three simulations described in this chapter were conducted to evaluate CYCLOPS as a model of infant perceptual development and they are akin to protocol analysis. With each infant experiment, the design was modelled as closely as possible so that CYCLOPS was faced with the same conditions as the infants. The behaviour which CYCLOPS produced was then compared with the findings for the infants. Although the problem of interpretation exists, the difficulties it presents were reduced in several ways. The visual world was designed to permit replication of the stimulus presentation conditions used in each experiment. Patterns could be exposed singly or in pairs in any position, and the start and end of an exposure could occur at any stage during an experimental session. A number of different patterns were used, and although they were not generally the same as those shown to infants, there is no good reason to suppose that infants would regard them differently from CYCLOPS.

One stimulus aspect which was not included and might have had an effect was extraneous visual stimulation, in particular the apparatus used to house the exposed stimuli. This provides infants with something else to look at, but CYCLOPS could only see the exposed patterns. It is unlikely that this omission would have been significant for the Fantz simulation as the infant results showed that they spent nearly all of the exposure time fixating the stimuli (Fantz, 1966). Similarly for the Fagan simulation, the recognition exposures were so short that they would have been no time for the infants to look at the stimuli and then to examine the surroundings. These surroundings are always made plain and un-interesting in such experiments to encourage the infants only to look at the stimuli.

The Caron and Caron simulation was the one case in which the lack of extraneous stimuli may have had an effect. Here the infants were only confronted with one stimulus, but they did not look at it for the duration of an exposure, especially when it had been repeatedly shown. In these circumstances they may well have been looking at something else, but CYCLOPS was only able to look away while making blind moves and these quickly returned its eye to fixate the pattern. However, it might be expected that if extraneous stimuli were included for CYCLOPS, the decline in looking at the repeated patterns would still have been achieved. The new, varied patterns would still have received long looks since the mean length per look and the length of the first look should remain un-affected. Only the number of looks and total amount of looking would be less because some time would be spent examining the extraneous stimuli.

On the behavioural side of the simulations the only interpretation which was made concerned the measurement of the amount of looking at a pattern. The infant measures were temporal, but no such measure would have been suitable for CYCLOPS without introducing too many arbitrary assumptions. The solution adopted was to measure the amount of looking by counting the number of fixations which were made. Although there is no information about the number of fixations infants make in these experiments, such a measure does relate to the duration of looking (Loftus, 1972). Although differences do occur in the duration of individual fixations (Gould and Dill, 1969), a mean duration of 300 milliseconds had been reported on a number of occasions (Mackworth and Bruner, 1970, Mackworth and Morandi, 1967). This suggests that it is not unreasonable to suppose that the duration of a look is related to the number of fixations which are made.

The comparison between the simulated results for CYCLOPS and the experimental results for the infants shows that both produce similar looking behaviour under the same conditions. These results may be summarized as follows:-

a) CYCLOPS and infants demonstrate the recognition of a repeatedly exposed pattern by a decrease in the amount of looking at the pattern relative to one which is new and has not previously been exposed.

b) This effect is not shown by CYCLOPS or infants at all stages of development. When both are young and have had little or no visual experience, repeatedly exposed patterns are looked at for the same duration as new patterns. However, when CYCLOPS and infants have received some visual experience, differential looking is demonstrated.

c) CYCLOPS and infants are able to recognize patterns (by virtue of looking more at new patterns) both immediately after the repeated exposure to a pattern and following a delay. CYCLOPS and infants are able to retain the memory of a pattern for a period during which other patterns are exposed.

These results establish CYCLOPS as a valid model of the development of infant looking behaviour during the first months of life.

In addition, two further points emerged from the simulations:-

d) A number of different measures of looking could be used with CYCLOPS (eg. total amount of looking, mean length per look, length of first look), and the effects listed above were demonstrated with each. Some measures produced clearer differences than others, particularly the length of the first look. Unfortunately the infant experiments reported only one or two of these measures, and the simulations suggest it is more useful to include as many different measures of looking as possible.

e) It was discovered that altering the length of the discrepancy index would produce individual differences with CYCLOPS in the style of looking. A long discrepancy index resulted in longer looks but decreased their number, while a short index produced short looks which were increased in number. These styles of looking resembled infants described as slow and fast tempo. The model embodied in CYCLOPS may serve to explain both the general characteristics of infant looking (listed in a-c) and these particular individual differences.

CHAPTER 8

A FINAL DISCUSSION

1. Theory and computer model.

CYCLOPS is a computer model which mimics the development of looking behaviour of infants while learning and recognizing patterns. The model is based on a theory concerning the role of eye movements in the development of pattern recognition which was proposed in the first three chapters of this thesis. Briefly, this theory makes the following points. The recognition of patterns large enough to require several fixations is achieved by the acquisition of scanning habits in which fixations are made in the same order as they originally appeared. The record of a pattern in memory contains two sorts of information; the features detected on the fovea at each fixation and the location of the peripheral region which is to be fixated. These two components are combined as analyzers and recognition is achieved by successfully predicting for each fixation which analyzer will match the current input. These predictions are obtained by recording the first-order sequential dependencies between the analyzers which match the input at each successive fixation. Fixations re-appear in the same order because each matching analyzer specifies which peripheral region is the target for the following fixation.

In order to control the length of a sequence of fixations (ie. the amount of looking a pattern receives), an assessment is made of the amount of discrepancy between a fixation sequence and the predictions in memory. If there is no discrepancy (ie. the sequence is familiar), the sequence will be short. If the sequence is extremely discrepant (ie. totally new) it will again be short, but if it is moderately discrepant (ie. partly new and partly familiar) the sequence will be long.

CYCLOPS is an interpretation of this theory, and the use of a computer program in expressing the theory has several distinct advantages. Firstly it allows the theory to be presented in a precise and explicit form. Considerable use is made of the concept of 'feature', and the model of the cortical processing of foveal input which the program contains shows clearly what a feature is for CYCLOPS and how it is produced. Similarly for other concepts such as 'analyzer' and 'discrepancy', the program enables precise definitions of these terms to be made. It is unfortunate that almost all but the simplest programs are extremely difficult to understand for anyone but the original programmer, but this difficulty can be surmounted by careful documentation. For this reason, three chapters (4, 5 and 6) were devoted to the description of the computer model.

A second advantage of a computer program is that it often requires the consideration of points which are either implicit or not covered in the theory. The most significant example of this with CYCLOPS is in the section concerning the oculomotor reflexes. The theory discusses the role of eye movements in pattern recognition, in particular the means by which information about eye movements is recorded in memory, but it does not make any statement about how eye movements are produced and controlled. Although the theory may be criticized on this point, it can be argued that such considerations are not essential because they do not affect the theory as it stands. The important point is that a region in the periphery must be selected as the target for a fixation, but the mechanisms which select the target region and execute the eye movement do not need to be elaborated.

The situation is very different for CYCLOPS which was intended to be a working model, and it was essential that oculomotor reflexes were included. The saccadic reflex was designed using what experimental information was available to model the system which controlled and initiated eye movements for scanning patterns. One finding which emerged from this exercise was the lack of such information concerning the scanning of complex stimuli. Locher and Nodine (1974) have recently made the same point, and there is a need for more research into this question. The blind move reflex was designed more along practical lines to allow CYCLOPS to quickly search the whole of the visual world and locate a pattern for fixation, but again there is little data on how subjects scan within large visual areas.

A third advantage of using a computer program to model a theory derives from running the program and observing the way it behaves. This will often reveal a deficiency in the model if it does not behave as expected. The computer is simply a tool since it produces quickly and accurately what could be derived by working through the program with pencil and paper. With the first tests of CYCLOPS it was apparent that the model was unable to reproduce scanpaths during recognition. Slight changes in the positioning of the fovea would alter the input so that predicted analyzers did not match and different peripheral regions were selected as targets for fixation. In addition, it often occurred that fixations alternated between only two regions and patterns were not sufficiently scanned.

It is unlikely that either of these problems would have been discovered if the program had not been run, and the use of the computer showed how the model could be improved. The saccadic reflex needed a small addition to prevent a region being re-fixated, but a new oculomotor reflex had to be included before CYCLOPS could reproduce scanpaths. This was the foveal centering reflex which ensured that the fovea was located centrally over contours after a region had been fixated. It was subsequently discovered in the literature that subjects also produce such corrective eye movements following a saccade. Thus running the computer program and the failure of CYCLOPS to behave as intended led to the elaboration of the model and the inclusion of a piece of behaviour which was completely unexpected.

2. The behaviour of CYCLOPS.

A further advantage of computer modelling is that the predictions and implications of a theory may be examined by observing how the model behaves. For the purposes of this discussion, CYCLOPS' behaviour can be divided into two sections. Firstly there is the detailed behaviour involving the production of individual fixations and the nature of fixation sequences, and secondly there is the grosser behaviour concerning the amount of looking and lengths of fixation sequences which patterns receive. The performance of CYCLOPS at these respectively microscopic and macroscopic levels will be considered in turn.

a) Detailed fixation behaviour.

CYCLOPS changes its point of fixation by selecting one region in the peripheral retina as a target, and executing an eye movement to bring that region onto the fovea. The selection of this target can be achieved in one of two ways; if there is no analyzer which matches the current input, the saccadic reflex computes the location of the target region, but when there is a matching analyzer the saccadic reflex is overruled and the analyzer specifies which is the peripheral target region.

The saccadic reflex operates with a 'centre of gravity' mechanism and computes as a target the region which lies in the directions containing greater numbers of active peripheral regions. For example, if a number of peripheral regions to the left of the fovea are active and more regions in the outer ring are active than regions in the inner ring, the target will be selected from the regions in the outer ring. If all of these outer regions at the left are active (regions 1 to 5 in figure 22), the regions in the up and down positions will 'balance' and the central region (number 3) will become the target. When regions are active in mutually exclusive directions (left/right and up/down), the target will be selected in the direction containing the greater number of active regions. If two patterns of different sizes are shown to CYCLOPS, the larger at the left of the fovea producing more active peripheral regions than the smaller on the right, the left-hand pattern will be fixated.

This fixation behaviour requires that the saccadic reflex is 'disconnected' from experience and the influence of analyzers. When analyzers match the current input and the peripheral target regions are analyzer-determined, the locations of fixations can differ considerably from the locations produced by the saccadic reflex alone. If CYCLOPS is presented with two patterns in close proximity, the saccadic reflex will usually produce a sequence of fixations on both patterns. However, if one of the patterns has been presented at an earlier stage, the analyzers acquired during the previous exposure will result in most of the sequence being confined to that one pattern. An example of this was shown in figures 34 and 35.

The effects of experience appear typically as the reproduction of scanpaths during recognition. Predicting which analyzer will match the current input ensures that the correct analyzers are selected. Because analyzers specify a peripheral target region, scanpaths will be reproduced. It should be pointed out that in some cases recording the peripheral target regions is not essential as the saccadic reflex would reproduce the original series of fixations as a matter of course. This will only happen if the stimulus conditions are un-altered in any way as changes in the peripheral configuration would result in different regions being selected as targets. For example, if the saccadic reflex alone was attempting to reproduce scanpaths, presenting the pattern alongside some other pattern would alter the peripheral configuration and thus the series of fixations. Similarly, changing a pattern in small ways (such as removing a corner) would also alter the peripheral configuration, and CYCLOPS would not be able to produce the original fixation sequence. Letting analyzers overrule the saccadic reflex is important in this case since it allows CYCLOPS to detect the change in the pattern by following the original scanpath until the changed region is fixated.

Several examples of the reproduction of scanpaths were shown in Chapter 5 (figures 37-39), and although CYCLOPS was able to reproduce some scanpaths exactly, it was discovered that considerable variability could be shown. The influence of the discrepancy index affected the length of a sequence so the initial scanpath could be long, but subsequent scanpaths could be much shorter. While later sequences would reproduce a part of the original, they would not have any fixations in common with each other. This could provide an explanation for the failure in some cases to detect scanpaths in a subject's looking (Noton and Stark, 1971a, 1971b), a result which was not predicted but was discovered as a property of the model in the course of running it on a computer.

Variations in scanpaths would also occur if the initial fixations of CYCLOPS were made on regions not previously fixated. In this situation CYCLOPS would make what may be termed a series of 'exploratory' fixations which had not previously occurred. CYCLOPS would then fixate a region which had been fixated before, and subsequently part of the original scanpath would be reproduced. Although CYCLOPS is designed to recognize patterns with the reproduction of scanpaths, it does not behave in a stereotyped manner and the variations in fixation sequences can be remarkably likelike.

It was also found that CYCLOPS would exhibit individual differences in scanpaths produced for the same patterns. If individual versions of CYCLOPS had acquired differing sets of analyzers depending on their history of visual experience, these would be used to match the input while scanning and so produced individual scanpaths. Although each separate version would reproduce a scanpath during recognition, its exact form depended on the individual.

b) Amount of looking at patterns.

It was essential that some means of controlling the lengths of fixation sequences was included to prevent the oculomotor reflexes producing endless fixation of a pattern. In order to achieve a model of infant looking behaviour, the discrepancy principle was incorporated to effect such a control. This principle specifies a curvilinear relation between the length of a fixation sequence and the degree to which it is discrepant with the predictions in memory. However, discrepancy is an ambiguous concept since an exact definition requires some statement about the representation of patterns in infant memory and how the amount of discrepancy between a fixation sequence and a representation may be assessed.

The study of stimulus representation in infant memory has only just begun and current explanations tend to be at a descriptive level. Kagan (1971) suggested that a schema representing a stimulus records the salient stimulus elements in terms of their number, form, shape and orientation, and their relationships with one another. If any of these elements or their relationships are altered, the altered stimulus is discrepant with the schema. Kagan also put forward an explanation for the operation of the discrepancy principle -

'The long fixation to a stimulus that represents an optimal discrepancy may derive from the fact that it takes time to match the event to an existing schema ... As long as the search for the match continues, attention remains riveted on the event. Familiar events find their match quickly and elicit short fixations. Novel events, with no resemblance to a schema, have a similar result for a different reason.' (Kagan, 1971, p.62).

The problem with this explanation is that it is still not clear what discrepancy is and how it is detected by the infant. How does the infant decide which are the salient elements of a stimulus and how does he record them. What are the processes involved in attempting to match a schema with a stimulus; are the individual elements examined and compared or is a stimulus treated as a whole. In addition to these criticisms, the explanation for the determinants of different amounts of looking seems arbitrary. Neither an optimally discrepant stimulus nor one which is novel exactly match any schema, but why should the search for a match continue in one case, but be given up so quickly in the other. These problems are bound to arise if no detailed explanation is provided about the representation of patterns in a schema and the process by which a pattern is matched with a schema and discrepancy detected.

CYCLOPS is able to avoid these difficulties because it includes an explicit description of the recording and subsequent recognition of patterns. Matching a pattern with the contents of memory involves making a number of fixations and predicting for each which analyzer will match the current input. The amount of discrepancy arising between a series of fixations and the predictions in memory is recorded by the position of a pointer along the discrepancy index. Looking will continue all the while the pointer remains between the ends of the index, but is terminated by a blind move when the pointer moves beyond either end. The movement of the pointer is determined by the success or failure of predicting the matching analyzer, and it is the amount of success and failure during a series of fixations which indicates the amount of discrepancy. If the sequence is not discrepant, each prediction will match the input and the pointer will move beyond the lower end. However, if the sequence is moderately discrepant, some predictions will match and some will mis-match and the pointer will remain between the two ends. Discrepancy is exactly defined in terms of the outcomes of predictions and the effects on looking follow directly from this.

These effects were demonstrated by the experiments reported in Chapter 6. In these experiments, the amount of discrepancy encountered while looking at a standard pattern was varied by the prior exposure of a pattern having some degree of similarity to the standard. The prior exposure of a pattern identical to the standard produced the least amount of looking at the standard during testing. This condition allowed a set of matching predictions to be acquired and there was no discrepancy. The prior exposure of a pattern similar to the standard produced more looking at the standard. Only a certain number of matches were acquired so that the fixation sequences were moderately discrepant with the predictions and hence lasted longer.

The amount of looking at the standard after exposure to a pattern very dissimilar to the standard was found to be influenced by the initial memory established during pre-training. In the first experiment it was expected that the prior exposure of a pattern dissimilar to the standard would only result in short looks at the standard during testing. This did not occur, the reason being that the initial memory was a source of some matching predictions which resulted in long sequences of fixations on the standard. In the second experiment this influence was discounted by the careful selection of standard patterns for which the initial memory did not contain matching predicitions. Under these conditions, looks at the standard in the test period were short following exposure of the dissimilar patterns in training.

The relevance of these results to infant experiments is that such studies typically assume the amount of discrepancy an infant encounters can be created by the experimenter with the exposure of patterns of various degrees of similarity to a standard (eg. Parry, 1973, Super et al., 1972). However, the experiments with CYCLOPS show that the infant's initial memory must also be taken into account as it may overrule the experimental conditions and the results may differ considerably from those which are expected.

The ability of CYCLOPS to mimic infant looking behaviour was shown in the reports of three simulated infant experiments in Chapter 7. Although the experiments differed in design, each was concerned with the recognition of stimuli as demonstrated by a decrease in looking at a repeatedly exposed stimulus. CYCLOPS produced such behaviour by virtue of the discrepancy index control of thelength of fixation sequences. If a new pattern was exposed and the fixation sequence was moderately discrepant with the predictions in memory, a large number of fixations were made. During the first looks, CYCLOPS acquired new analyzers and prediction lists with the result that further looks at the pattern became less discrepant and the length of each fell until a minimum was reached. This decline occurred with all fixation sequences that were initially moderately discrepant. Although the rate of decline varied, the looks reached the same minimum length when no discrepancy was encountered.

Accompanying this decline in the length of each look was an increase in the total number of looks made. If a pair of new patterns was exposed, CYCLOPS began by taking long looks with few movements from one pattern to another. Towards the end of an exposure this behaviour changed with the looks being shorter and far more were made between the two patterns. This effect was not reported in Chapter 7 but was observed during the familiarization exposures in the Fagan simulation.

This decline in looking was exploited in each of the simulated experiments to indicate the recognition of a pattern. However, CYCLOPS required a certain amount of prior visual experience before such differential looking at repeatedly exposed and new patterns could be shown. Without this experience it did not occur, though evidence for recognition was supplied in the form of the reproduction of scanpaths.

It was also discovered that CYCLOPS could produce individual differences in the style of looking by the variation of the length of the discrepancy index. Overall, each individual could produce the same kind of results, but they differed in the total amounts of looking and number of looks which were made. These styles resembled a dimension of infant behaviour called conceptual tempo (Kagan, 1971), and CYCLOPS suggested that differences among infants along this dimension could be explained as a function of the discrepancy principle.

3. Limitations of CYCLOPS.

Although CYCLOPS is able to produce looking behaviour resembling infants, there are a number of capabilities which are outside the scope of the model in its current form. Those which are most relevant are discussed below.

a) Forgetting.

When an analyzer or prediction list is established in memory it is retained unchanged and never lost. CYCLOPS does not forget something which is learned. However, there are some studies which indicate that visual memory in adults and infants may also operate at a similar level. Shepard (1967) and Haber (1970) have both shown that subjects can recognize pictures after long delays of days, weeks and even months. Fagan (1973) has shown the same ability with infants for periods up to 2 weeks. Although forgetting is likely to occur, these findings suggest it is not a serious omission for CYCLOPS.

One possible explanation of forgetting when it does occur is interference between similar items in memory. The seemingly indestructable memory described above may be due to recording distinctive pattern features. If patterns are similar and do not contain such distinguishing features, the record of the pattern seen most recently may displace existing memories. This has been suggested as occurring with infants by Fagan (1973), but the results are not clear and further research is needed. CYCLOPS could be modified to produce interference effects in two ways. Incorrect predictions could be erased from memory and be replaced with correct versions, or the ordering of entries in prediction lists could be altered. The entries which occur first in a prediction list have priority over later ones when the analyzers to which they refer are compared with the current input. If priority was determined instead by either the frequency or recency of matching an analyzer, recognition would be interfered with especially for similar patterns.

b) Pattern identification.

CYCLOPS is able to recognize patterns by reproducing scanpaths and taking short looks, but is unable to identify a pattern. If two patterns are familiar and both are recognized, CYCLOPS is unable to supply each with a different name. In its present form, CYCLOPS could not be used to identify letters of the alphabet even though they could all be recognized. Although the distinction between pattern recognition and identification is not generally made, it is implicit in all the infant studies reported in this thesis. Recognition is shown by a decline in the amount of looking at a pattern, but there is no way in such experiments for infants to communicate that one familiar pattern is identified as different from another.

CYCLOPS is unable to identify patterns because sequences of fixations are not stored separately but only as first order sequential dependencies. One method of providing CYCLOPS with the ability to identify patterns would be to assign a different label to each predicted analyzer in a sequence. Although some predictions would be assigned several labels because they belonged to more than one fixation sequence, the correct identity of a sequence could be determined by only retrieving the one label consistently attached to each matching prediction.

c) Recognition without eye movements.

Although CYCLOPS recognizes patterns with the reproduction of sequences of fixations, this does not rule out the possibility of recognition in the absence of eye movements. However, recognition would be limited since in this situation CYCLOPS could only attempt to find one analyzer to match the input occurring during the single fixation. If one was found, CYCLOPS would regard the pattern as familiar; if none was found to match the input, CYCLOPS would have to regard the pattern as new.

Clearly, the ability of CYCLOPS to make correct decisions after making only a single fixation would depend very much on which region of a pattern was fixated. Some patterns which have previously been exposed have regions which have not been fixated and for which no matching analyzer exists. A single fixation on such a region would cause CYCLOPS to class as new a pattern which should be recognized. Conversely, some patterns which have not been exposed contain regions for which matching analyzers do exist, and fixation of these would cause CYCLOPS to class the pattern as familiar.

d) Recognition of patterns which are altered in size or rotated.

Although CYCLOPS may be able to recognize patterns when restricted to making only one fixation, changes due to alterations in size or rotation pose serious problems. CYCLOPS is able to cope with slight variations in the size of patterns by virtue of the foveal centering reflex. This is able to position the fovea correctly, but the changes in size can only be slight, in the order of 2 or 3 visual world units. Changes greater than this would alter the peripheral configuration during a fixation and the predicted analyzers would fail to match.

At the other extreme there are patterns which have been reduced in size, in particular patterns which originally were large enough to cover the peripheral retina, but have been reduced until they fit entirely within the fovea. Again CYCLOPS could not recognize a pattern transformed in this way since the peripheral input would be lacking and the whole pattern would be processed as one foveal feature list.

Unfortunately there is little information in the literature about eye movements and perception or the development of recognition in infants which could be of use in overcoming this problem with CYCLOPS. In most studies the stimuli which are used are not altered in size and are presented at the same distance each time from the subject. It is not known whether scanpaths are still repeated or whether an infant can recognize a stimulus when it is doubled in size. Bower (1964) has shown that infants would fail to produce a conditioned response when the stimulus (a three-dimensional cube) was altered in physical size. While this suggests a failure to recognize, it is not certain whether this would also occur with the two-dimensional stimuli that are used in most infant experiments.

Although this is a serious difficulty with CYCLOPS, it is possible to isolate the source of the problem. Recording the peripheral target region provides two kinds of information; the direction of the target region from the fovea and its distance. When patterns are altered in size yet are large enough to cover some of the peripheral retina, the information about the direction of the target region may still be used, but the distance of the region from the fovea is altered. If some means of estimating the overall size of a pattern could be included, this distance information could be scaled up or down to ensure the correct peripheral region was selected as target.

The problem with patterns which are reduced in size so much that they fit completely onto the fovea is rather different. Here no eye movements can be made, but one solution which Noton and Stark (1971a) proposed was that some form of internal scanning might occur. However, CYCLOPS would have to be altered to a very different model to achieve anything like this. The structure of analyzers would need drastic modification as a pattern which was so small would be represented completely by a foveal feature list and there would be no peripheral input at all.

CYCLOPS is also unable to recognize a pattern which is rotated, again because predicted analyzers would not match the altered input. This difficulty is not unique to CYCLOPS since infants fail to recognize rotated or inverted patterns (McGurk, 1970). Adult subjects also find this a problem, for example with inverted faces or writing (Hochberg, 1972). When a pattern is rotated, the information about the distance of a peripheral target region from the fovea may still be used, but it is the direction of the target which is altered. If some means of detecting the orientation of a pattern could be employed, it might be possible to adjust the direction of the peripheral target region from the fovea, a suggestion made by Noton (1969). The difficulty is that it is not clear how the orientation of a pattern may be determined without knowing what the pattern might be. Again, it is not known whether a scanpath is repeated in a rotated form if a pattern is rotated, or whether the scanpath is entirely different.

4. Conclusion.

The aim of this thesis has been to present a computer model which is able to provide an account of the early stages of infant perceptual development. The role of the computer in this exercise was not that of a 'stupid servant' as it has sometimes been described, but more that of a 'demanding master'. In this role it required the exact formalization of the theory and therefore the inclusion of several elements not previously considered which provided a more complete explanation. It was able to show deficiencies in the model, and when these were corrected it showed that the model could mimic the development of pattern recognition in infants. Although it is often felt that a simulation cannot tell us anything which we did not already know because the computer only does what it is programmed to do, this was not the case and several findings emerged which had not been anticipated. Computer simulation is still a new technique in psychology. but it is hoped that the results obtained with CYCLOPS will help to support its inclusion as another useful tool for the study and explanation of behaviour.

APPENDIX 1.

A COMPLETE LISTING OF THE PROGRAM CYCLOPS.

1. Introduction.

The program is written in Fortran for the MNF (Minnesota Fortran) compiler, and was run on the University of London CDC 6600 computer. The listing includes all major components of CYCLOPS, and various 'housekeeping' routines which are not part of the model but are necessary for the operation of the program. The program has been edited to reduce its length, but nothing significant has been left out. The parts which have been excluded from this listing are concerned with the detailed analysis of CYCLOPS' behaviour (routines which computed the several fixation measures), and a substantial part of the pattern library. Three examples of patterns are included, but the remainder were discarded since their exact form is not essential to the operation of the program.

The listing is complete as it stands, and would run if provided with suitable input. A sample input is included in section 4, and section 5 indicates the form of output which would be printed. The Fortran is fairly standard for most systems, though there may be individual differences in the nature of the input/output format statements. The MNF compiler permits a variable name to contain up to 7 characters (eg. MATRX21) which is not common to all systems, and the program would need adapting if the limit was only 6 characters (eg MATX21).

The complete program (including the components excluded in the listing) occupied 31K of core storage in the 6600 machine. Run times were reasonably fast; for example one session in the Fantz simulation (10 exposures of pattern pairs) took on average 30 seconds of central processing time, and a session in the Caron & Caron simulation (15 exposures of a single pattern) took an average of 34 seconds.

CYCLOPS is one complete program, and does not contain separate subroutines. Comments are placed at the start of blocks of program to indicate the purpose of each block. These correspond with the descriptions of the program in chapters 4, 5 and 6, and also with the flow diagrams of figures 41 and 42.

2. Brief descriptions of the Functions of the Arrays and Variables used in the program.

Array	Size	Function
MATRX1	(120,120)	Visual world.
MATRX2	(10,10)	Foveal ganglion cells.
MATRX3	(24,3)	Peripheral retinal regions. Also contains data used by saccadic reflex.
MATRX4	(6,8)	Vertical simple cells.
MATRX5	(8,6)	Horizontal simple cells.
MATRX6	(6,4)	Vertical complex cells.
MATRX7	(4,6)	Horizontal complex cells.
MATRX8	(5,4)	Vertical hypercomplex, lower-stopped.
MATRX9	(5,4)	Vertical hypercomplex, upper-stopped.
MATRX10	(4,5)	Horizontal hypercomplex, left-stopped.
MATRX11	(4,5)	Horizontal hypercomplex, right-stopped.
MATRX15	(8,2)	Contains data used by saccadic reflex.
MATRX19	(7)	Foveal feature list.
MATRX20	(20,35)	Records FFLs and the analyzer numbers of which each FFL is a member.
MATRX21	(120,18)	Records analyzers (FFL & PTR) and prediction lists.
MATRX25	(13,30)	Records details of each fixation for a sequence of 30 fixations.
MATRX26	(10,2)	Used by foveal centering reflex computation.
MATRX28	(40,40)	Contains a copy of a pattern for insertion into visual world.
MATRX29	(70,5)	Contains pattern input and removal information for duration of run.

Variable	Function
ANA	Analyzer matching current input.
BLIND	Records whether a series of fixations has started, 0 = no, 1 = yes.
DISCIN	Position of pointer on discrepancy index.
ENOUGH	Total number of fixations to be made during a run. When JANE equals ENOUGH, the run is terminated.
FFL	Foveal feature list for current input.
HFN	Records the number of the first available row in MATRX21 in which a new analyzer may be stored. HFN incremented +1 when new analyzer created.
HITHR	Upper limit of discrepancy index.
IJI	Number of data cards to read containing pattern input information.
INMO	The peripheral region fixated previously.
JANE	Records the number of fixations which have currently been made.
KA, MA	Column and row co-ordinates (respectively) of the top, left-hand corner of the fovea in the visual world.
LOTHR	Lower limit of discrepancy index.
MOVE	Incremented + 1 each time a fixation is made. Re-set to 0 after 30 fixations. Fixation data is printed out when MOVE equals 30.

Variable	Function
MSMTCH	Movement of pointer up discrepancy index following a mismatch.
MTCH	Movement of pointer down discrepancy index following a match.
PAN	Analyzer matching previous input.
PRED	Prediction list for current matching analyzer.
PTR	Peripheral target region.
SCAN	Records the direction of a sequence of blind moves. 0 = clockwise. 1 = anti-clockwise.

3. The Program Listing

```
       PROGRAM CYCLOPS (INPUT,OUTPUT)
C      ALLOCATE STORAGE ETC.
       COMMON MATRX1(120,120)
       DIMENSION MATRX2(10,10),MATRX3(24,3),MATRX4(6,8),
      1MATRX5(8,6),MATRX6(6,4),MATRX7(4,6),MATRX8(5,4),
      1MATRX9(5,4),MATRX10(4,5),MATRX11(4,5),MATRX15(8,2),
      1MATRX19(7),MATRX20(20,35),MATRX21(120,18),MATRX25(13,30),
      1MATRX26(10,2),MATRX28(40,40),MATRX29(70,5)
       DIMENSION PRED(16),MATCH(10)
       INTEGER BLIND,PRED,FFL,ANA,HFN,PAN,SCAN,ON,OFF
      1HITHR,ENOUGH,DISCIN
C      INITIALIZING
       DO 100 I=1,120
       DO 102 J=1,120
102    MATRX1(J,I)=0
100    CONTINUE
       DO 110 I=1,16
110    PRED(I)=0
       DO 103 I=1,35
       DO 104 J=1,20
104    MATRX20(J,I)=0
103    CONTINUE
       DO 108 I=1,18
       DO 109 J=1,120
109    MATRX21(J,I)=0
108    CONTINUE
       SCAN=0
       JANE=0
       MOVE=0
       ANA=0
       PAN=0
       FFL=0
```

```
      INMO=0
      JAT=0
      BLIND=0
      HFN=1
C     READ INPUT - THE VALUES OF SEVERAL PARAMETERS
C     ARE SET AT THIS STAGE. THESE ARE: NO. OF DATA
C     CARDS CONCERNING PATTERNS AND THE VISUAL WORLD,
C     LENGTH OF RUN, INITIAL POSITION OF FOVEA, LOWER
C     AND UPPER LIMITS OF DISCREPANCY INDEX, MOVEMENT
C     OF POINTER DOWN AND UP INDEX FOLLOWING MATCH
C     AND MISMATCH RESPECTIVELY, NO. OF LINES OF
C     FIXATION DATA TO PRINT OUT, INITIAL POSITION OF POINTER.
      READ 120,IJI,ENOUGH
      READ 120,KA,MA
      READ 120,LOTHR,HITHR
      READ 120,MTCH,MSMTCH
      READ 120,NPRIN,DISCIN
C     A NUMBER OF DATA CARDS ARE READ WHICH INDICATE
C     THE PATTERNS TO BE INSERTED AND DELETED FROM
C     THE VISUAL WORLD, WHEN THIS IS TO OCCUR AND WHERE
C     THEY ARE POSITIONED.
      DO 128 J=1,IJI
128   READ 126,(MATRX29(J,I),I=1,5)
C     READ DATA CONCERNING THE SACCADIC REFLEX COMPUTATION
C     OF A PERIPHERAL TARGET REGION & EXECUTION OF AN
C     EYE MOVEMENT.
      DO 107 J=1,24
107   READ 120,MATRX3(J,2),MATRX3(J,3)
      DO 127 J=1,8
127   READ 121,MATRX15(J,2)
```

```
C     PRINTOUT OF FIXATION INFORMATION. THE NO. OF THE
C     FIXATION, POSITION OF THE FOVEA, CONTENTS OF
C     PREDICTION LIST, ANALYZER, FFL, PTR AND POSITION
C     OF DISCREPANCY INDEX POINTER ARE ALL RECORDED.
      PRINT 132
134   IF(MOVE.LT.30)GO TO 136
      PRINT 123
      DO 138 J=1,NPRIN
      IF(J.EQ.1)PRINT 149,(MATRX25(J,I),I=1,30)
      IF(J.EQ.2)PRINT 141,(MATRX25(J,I),I=1,30)
      IF(J.EQ.3)PRINT 150,(MATRX25(J,I),I=1,30)
      IF(J.GE.4.AND.J.LE.8)PRINT 143,(MATRX25(J,I),I=1,30)
      IF(J.EQ.9)PRINT 144,(MATRX25(J,I),I=1,30)
      IF(J.EQ.10)PRINT 145,(MATRX25(J,I),I=1,30)
      IF(J.EQ.11)PRINT 146,(MATRX25(J,I),I=1,30)
      IF(J.EQ.12)PRINT 147,(MATRX25(J,I),I=1,30)
      IF(J.EQ.13)PRINT 148,(MATRX25(J,I),I=1,30)
138   CONTINUE
      MOVE=0
C     HAS RUN ENDED YET?
136   IF(JANE.EQ.ENOUGH)GO TO 160
C     ENTER PATTERNS INTO VISUAL WORLD
      DO 1102 J=1,IJI
      IF(MATRX29(J,1).GT.JANE)GO TO 1122
      IF(MATRX29(J.1).NE.JANE)GO TO 1102
      JS=MATRX29(J.3)
      IS=MATRX29(J,4)
      JST=JS+39
      IST=IS+39
      INE=MATRX29(J,5)
      DO 1120 IX=1,40
      DO 1142 JX=1,40
```

```
1142  MATRX28(JX,IX)=0
1120  CONTINUE
C     CASE
      IF(INE.EQ.1)GO TO 3065
C     CROSS
      IF(INE.EQ.2)GO TO 3012
C.    LETTER U
      IF(INE.EQ.3)GO TO 3018
C     PATTERN LIBRARY - ONLY 3 PATTERNS ARE INCLUDED
C     CASE
3065  DO 3066 I=1,30
      DO 3067 JX=11,30
3067  MATRX28(JX,I)=1
3066  CONTINUE
      DO 3068 I=4,27
      DO 3069 JX=1,10
3069  MATRX28(JX,I)=1
3068  CONTINUE
      DO 3070 I=10,21
      DO 3071 JX=6,10
3071  MATRX28(JX,I)=0
3070  CONTINUE
      GO TO 1106
C     CROSS
3012  DO 3013 I=11,20
      DO 3014 JX=1,30
      MATRX28(JX,I)=1
3014  MATRX28(I,JX)=1
3013  CONTINUE
      GO TO 1106
C     LETTER U
3018  DO 3019 I=1,30
```

```
      DO 3020 JX=1,30
3020  MATRX28(JX,I)=1
3019  CONTINUE
      DO 3021 I=11,20
      DO 3022 JX=1,20
3022  MATRX28(JX,I)=0
3021  CONTINUE
      GO TO 1106
1102  CONTINUE
1122  MOVE=MOVE+1
      JANE=JANE+1
1106  II=0
      DO 1108 IX=IS,IST
      II=II+1
      JJ=0
      DO 1110 JX=JS,JST
      JJ=JJ+1
      IF(MATRX28(JJ,II).GT.0.AND.MATRX29(J,2).EQ.1)
     1MATRX1(JX,IX)=0
      IF(MATRX28(JJ,II).GT.0.AND.MATRX29(J,2).EQ.0)
     1MATRX1(JX,IX)=1
1110  CONTINUE
1108  CONTINUE
C     PATTERN PRE-PROCESSING
C     FOVEAL GANGLION CELL FIELDS
216   KAT=KA
      MAT=MA
      KAS=KAT+9
      MAS=MAT+9
      KAR=0
      DO 218 I=KAT,KAS
      KAR=KAR+1
      MAR=0
      DO 220 J=MAT,MAS
```

```
      MAR=MAR+1
      IX=I+1
      JX=J+1
      JUDGE=0
      JIM=MATRX1(JX,IX)
      IC=I+2
      JC=J+2
      MATRX2(MAR,KAR)=0
      DO 222 IRE=I,IC
      DO 224 JUB=J,JC
      IF(JUDGE.EQ.3)GO TO 226
      IF(MATRX1(JUB,IRE).NE.JIM)JUDGE=JUDGE+1
224   CONTINUE
222   CONTINUE
      GO TO 220
226   MATRX2(MAR,KAR)=1
220   CONTINUE
218   CONTINUE
C     FOVEAL CENTERING
      IF(JAT.GT.1)GO TO 228
      DO 200 J=1,10
      MATRX26(J,1)=0
200   MATRX26(J,2)=0
      JAS=0
      JAP=0
      JASX=0
      JAPX=0
      DO 202 I=1,10
      DO 204 J=1,10
      MATRX26(I,2)=MATRX26(I,2)+MATRX2(J,I)
204   MATRX26(J,1)=MATRX26(J,1)+MATRX2(J,I)
202   CONTINUE
      DO 206 J=1,10
```

```
      IF(MATRX26(J,1).LT.4)GO TO 210
      IF(MATRX26(J,1).GT.JASX)GO TO 208
      IF(MATRX26(J,1).NE.JASX)GO TO 210
      JAS=(JAS+J)/2
      GO TO 210
208   JASX=MATRX26(J,1)
      JAS=J
210   IF(MATRX26(J,2).LT.4)GO TO 206
      IF(MATRX26(J,2).GT.JAPX)GO TO 214
      IF(MATRX26(J,2).NE.JAPX)GO TO 206
      JAP=(JAP+J)/2
      GO TO 206
214   JAPX=MATRX26(J,2)
      JAP=J
206   CONTINUE
      KAL=0
      MAL=0
      IF(JAP.GT.0)KAL=JAP-6
      IF(JAS.GT.0)MAL=JAS-6
      JAT=JAT+1
      IF(KAL.EQ.0.AND.MAL.EQ.0)GO TO 228
      KA=KA+KAL
      MA=MA+MAL
      IF(KA.GT.109)KA=109
      IF(MA.GT.109)MA=109
      IF(KA.LT.1)KA=1
      IF(MA.LT.1)MA=1
      GO TO 216
C     VISUAL CORTEX
C     VERTICAL SIMPLE CELLS
228   JAT=0
      DO 230 ID=1,8
      DO 232 JD=1,6
```

```
        NIP=0
        IE=ID+3
        JE=JD+4
        IF=ID+1
        IG=ID+2
        DO 234 KLOP=JD,JE
        IF(MATRX2(KLOP,ID).GT.0)NIP=NIP-1
        IF(IE.GT.10)GO TO 236
        IF(MATRX2(KLOP,IE).GT.0)NIP=NIP-1
236     IF(MATRX2(KLOP,IF).GT.0)NIP=NIP+1
        IF(MATRX2(KLOP.IG).GT.0)NIP=NIP+1
234     CONTINUE
        MATRX4(JD,ID)=0
        IF(NIP.GT.6)MATRX4(JD,ID)=1
232     CONTINUE
230     CONTINUE
C       HORIZONTAL SIMPLE CELLS
        DO 238 ID=1,6
        DO 240 JD=1,8
        NIP=0
        IE=ID+4
        JE=JD+3
        JF=JD+1
        JG=JD+2
        DO 242 KLOP=ID,IE
        IF(MATRX2(JD,KLOP).GT.0)NIP=NIP-1
        IF(JE.GT.10)GO TO 244
        IF(MATRX2(JE,KLOP).GT.0)NIP=NIP-1
244     IF(MATRX2(JF,KLOP).GT.0)NIP=NIP+1
        IF(MATRX2(JG,KLOP).GT.0)NIP=NIP+1
242     CONTINUE
        MATRX5(JD,ID)=0
        IF(NIP.GT.6)MATRX5(JD,ID)=1
```

```
240   CONTINUE
238   CONTINUE
C     CLEAR FOVEAL FEATURE LIST. THIS ENSURES NO
C     ENTRIES REMAIN FROM THE PREVIOUS FIXATION.
C     THE NEW ENTRIES IN THE FFL WILL BE MADE AS
C     EACH SET OF CORTICAL CELLS IS PROCESSED.  AT
C     THE END OF THIS SECTION, THE FFL IS COMPLETE.
      DO 246 I=2,7
246   MATRX19(I)=0
C     VERTICAL COMPLEX CELLS
      NAF=0
      DO 248 MIF=1,7,2
      NAF=NAF+1
      LAP=0
      JUC=MIF+1
      DO 253 NIF=1,6
      MATRX6(NIF,NAF)=0
      IF(MATRX4(NIF,MIF).EQ.0.AND.MATRX4(NIF,JUC).EQ.0)
     1GO TO 253
      MATRX6(NIF.NAF)=1
      LAP=LAP+1
253   CONTINUE
      IF(LAP.EQ.0)GO TO 248
      MATRX19(2)=MATRX19(2)+1
248   CONTINUE
C     HORIZONTAL COMPLEX CELLS
      DO 252 MIF=1,6
      NAF=0
      DO 254 NIF=1,7,2
      NAF=NAF+1
      MATRX7(NAF,MIF)=0
      IF(MATRX5(NIF,MIF).EQ.0.AND.MATRX5(JUC,MIF).EQ.0)
     1GO TO 254
```

```
      MATRX7(NAF,MIF)=1
254   CONTINUE
252   CONTINUE
      DO 256 J=1,4
      LAP=0
      DO 258 I=1,6
      IF(MATRX7(J,I).GT.0)LAP=LAP+1
258   CONTINUE
      IF(LAP.EQ.0)GO TO 256
      MATRX19(3)=MATRX19(3)+1
256   CONTINUE
C     VERTICAL HYPERCOMPLEX LOWER STOPPED
      DO 260 I=1,4
      DO 262 J=1,5
      JJ=J+1
      MATRX8(J,I)=0
      IF(MATRX6(JJ,I).GT.0)GO TO 262
      IF(MATRX6(J,I).EQ.0) GO TO 262
      MATRX8(J,I)=1
      MATRX19(4)=MATRX19(4)+1
262   CONTINUE
260   CONTINUE
C     VERTICAL HYPERCOMPLEX UPPER STOPPED
      DO 264 I=1,4
      DO 266 J=1,5
      JJ=J+1
      MATRX9(J,I)=0
      IF(MATRX6(J,I).GT.0)GO TO 266
      IF(MATRX6(JJ,I).EQ.0)GO to 266
      MATRX9(J,I)=1
      MATRX19(5)=MATRX19(5)+1
266   CONTINUE
264   CONTINUE
```

```
C       HORIZONTAL HYPERCOMPLEX LEFT STOPPED
        DO 268 I=1,5
        DO 270 J=1,4
        II=I+1
        MATRX10(J,I)=0
        IF(MATRX7(J,I).GT.0)GO TO 270
        IF(MATRX7(J,II).EQ.0)GO TO 270
        MATRX19(6)=MATRX19(6)+1
270     CONTINUE
268     CONTINUE
C       HORIZONTAL HYPERCOMPLEX RIGHT STOPPED
        DO 272 I=1,5
        DO 274 J=1,4
        II=I+1
        MATRX11(J,I)=0
        IF(MATRX7(J,II).GT.0)GO TO 274
        IF(MATRX7(J,I).EQ.0)GO TO 274
        MATRX19(7)=MATRX19(7)+1
        MATRX11(J,I)=1
274     CONTINUE
272     CONTINUE
C       PERIPHERAL RETINAL FIELDS
        DO 292 I=1,24
292     MATRX3(I,1)=0
        ICX=KA-36
        ICOUNT=0
        DO 276 I=1,5
        ICX=ICX+12
        IRX=MA-36
        DO 278 J=1,5
        IRX=IRX+12
        IF(I.EQ.3.AND.J.EQ.3)GO TO 278
        ICOUNT=ICOUNT+1
        JCX=ICX
```

```
      JCE=JCX+12
      JRX=IRX
      JRE=JRX+12
      IF(JCX.LT.1)JCX=1
      IF(JRX.LT.1)JRX=1
      IF(JCE.GT.120)JCE=120
      IF(JRE.GT.120)JRE=120
      IF(JCE.LT.1)JCE=1
      IF(JRE.LT.1)JRE=1
      IF(JCX.GT.120)JCX=120
      IF(JRX.GT.120)JRX=120
      INDX1=0
      INDX2=0
      DO 282 MX=JCX,JCE,3
      DO 284 NX=JRX,JRE,3
      IF(MATRX1(NX,MX).EQ.0)INDX1=INDX1+1
      IF(MATRX1(NX,MX).EQ.1)INDX2=INDX2+1
      IF(INDX1.GT.5.AND.INDX2.GT.5)GO TO 286
284   CONTINUE
282   CONTINUE
      GO TO 278
286   MATRX3(ICOUNT,1)=1
278   CONTINUE
276   CONTINUE
C     LOCATE PERIPHERAL FIELD CORRESPONDING TO
C     PREVIOUS FIXATION AND SET IT TO ZERO
      IF(INMO.EQ.0)GO TO 308
      MATRX3(INMO,1)=0
C     RECORD DETAILS OF FIXATION FOR PRINTOUT
308   MATRX25(1,MOVE)=JANE
      MATRX25(2,MOVE)=KA
      MATRX25(3,MOVE)=MA
```

```
      DO 309 J=4,8
      JX=J-3
309   MATRX25(J,MOVE)=PRED(JX)
C     IS THERE A PREDICTION LIST?
      IF(PRED(1).EQ.0)GO TO 322
C     DOES ANY PREDICTED ANALYZER MATCH THE INPUT?
C     CHECK FOVEAL FEATURE LIST
      DO 364 J=1,10
364   MATCH(J)=0
      JAK=0
      DO 310 J=1,16
      IF(PRED(J).EQ.0)GO TO 312
      JX=PRED(J)
      JX=MATRX21(JX,1)
      DO 314 I=2,7
      IF(MATRX19(I).NE.MATRX20(I,JX))GO TO 310
314   CONTINUE
      JAK=JAK+1
      MATCH(JAK)=PRED(J)
      FFL=JX
310   CONTINUE
312   IF(MATCH(1).EQ.0)GO TO 326
C     CHECK PERIPHERAL TARGET REGION
      DO 316 J=1,10
      IF(MATCH(J).EQ.0)GO TO 326
      JX=MATCH
      PTR=MATRX21(JX,2)
      IF(MATRX3(PTR,1).EQ.0)GO TO 316
      ANA=MATCH
      GO TO 318
316   CONTINUE
      GO TO 326
C     MATCH - MOVE POINTER ONE STEP DOWN DISCREPANCY
```

```
C       INDEX

318     DISCIN=DISCIN-MTCH
        MATRX25(13,MOVE)=1

C       IS POINTER WITHIN LIMITS OF DISCREPANCY INDEX ?

319     IF(DISCIN.LT.LOTHR.OR.DISCIN.GT.HITHR)SCAN=SCAN+1
        IF(DISCIN.LT.LOTHR.OR.DISCIN.GT.HITHR)GO TO 360

C       COPY PREDICTION LIST BELONGING TO MATCHING ANALYZER

        DO 320 J=1,16
        JX=J+2
320     PRED(J)=MATRX21(ANA,JX)
        BLIND=0
        GO TO 350

C       HAS PATTERN SCANNING BEGUN YET ?

322     IF(BLIND.EQ.1)MATRX25(13,MOVE)=0
        IF(BLIND.EQ.1)GO TO 324

C       MISMATCH - MOVE POINTER ONE STEP UP DISCREPANCY
C       INDEX

        DISCIN=DISCIN+MSMTCH
        MATRX25(13,MOVE)=2
        GO TO 324

C       MISMATCH - MOVE POINTER ONE STEP UP DISCREPANCY
C       INDEX

326     DISCIN=DISCIN+MSMTCH
        MATRX25(13,MOVE)=2

C       DOES ANY ANALYZER MATCH THE INPUT ?
C       CHECK FOVEAL FEATURE LIST

324     DO 328 I=1,35
        DO 330 J=1,7
        IF(MATRX20(1,I).EQ.0)GO TO 332
```

```
      IF(J.EQ.1)GO TO 330
      IF(MATRX19(J).NE.MATRX20(J,I))GO TO 328
      IF(J.LT.7)GO TO 330
      FFL=I
      GO TO 334
332   DO 337 JJ=1,7
337   MATRX20(JJ,I)MATRX18(JJ)
      FFL=I
      GO TO 342
330   CONTINUE
328   CONTINUE
      GO TO 342
C     CHECK PERIPHERAL TARGET REGION
334   DO 336 I=8,20
      IF(MATRX20(I,FFL).EQ.0)GO TO 342
      JX=MATRX20(I,FFL)
      PTR=MATRX21(JX,2)
      IF(MATRX3(PTR,1).EQ.0)GO TO 336
      ANA=JX
      GO TO 338
336   CONTINUE
      GO TO 342
C     ADD NUMBER OF ANALYZER TO PREDICTION LIST OF
C     PREVIOUS ANALYZER
338   IF(PAN.EQ.0)GO TO 319
      DO 340 I=3,18
      IF(MATRX21(PAN,I).GT.0)GO TO 340
      MATRX21(PAN,I)=ANA
340   CONTINUE
      GO TO 319
C     IS POINTER WITHIN LIMITS OF DISCREPANCY INDEX ?
342   ANA=0
```

```
      IF(DISCIN.LT.LOTHR.AND.DISCIN.GT.HITHR)SCAN=SCAN+1
      IF(DISCIN.LT.LOTHR.AND.DISCIN.GT.HITHR)GO TO 360
C     IS PERIPHERY EMPTY ?
      DO 344 I=1,24
      IF(MATRX3(I,1).GT.0)GO TO 346
344   CONTINUE
      GO TO 360
C     SACCADIC REFLEX - COMPUTE PERIPHERAL TARGET
C     REGION
346   DO 347 I=1,8
347   MATRX15(I,1)=0
      DO 348 I=1,24
      IF(MATRX3(I,1).EQ.0)GO TO 348
      IX=MATRX3(I,2)
      JX=MATRX3(I,3)
      IF(IX.EQ.0)GO TO 349
      MATRX15(IX,1)=MATRX15(IX,1)+1
349   IF(JX.EQ.0)GO TO 348
      MATRX15(JX,1)=MATRX15(JX,1)+1
348   CONTINUE
      IX=0
      JX=0
      IF((MATRX15(1,1)+MATRX15(5,1)).GT.(MATRX15(2,1)+
     1MATRX15(6,1)))IX=1
      IF((MATRX15(1,1)+MATRX15(5,1)).LT.(MATRX15(2,1)+
     1MATRX15(6,1)))IX=2
      IF((MATRX15(3,1)+MATRX15(7,1)).GT.(MATRX15(4,1)+
     1MATRX15(8,1)))JX=3
      IF((MATRX15(3,1)+MATRX15(7,1)).LT.(MATRX15(4,1)+
     1MATRX15(8,1)))JX=4
      IZ=0
      JZ=0
      IF(IX.EQ.0.AND.JX.EQ.0)GO TO 382
```

```
      IF(IX.EQ.0)GO TO 384
      IF(IX.EQ.2)GO TO 386
      IZ=1
      IF(MATRX15(1,1).LT.MATRX15(5,1))IZ=5
      GO TO 384
386   IZ=2
      IF(MATRX15(2,1).LT.MATRX15(6,1))IZ=6
384   IF(JX.EQ.0)GO TO 388
      IF(JX.EQ.4)GO TO 390
      JZ=3
      IF(MATRX15(3,1).LT.MATRX15(7,1))JZ=7
      GO TO 388
390   JZ=4
      IF(MATRX15(4,1).LT.MATRX15(8,1))JZ=8
C     DETERMINE REGION TO BE FIXATED
388   DO 392 J=1,24
      IF(MATRX3(J,1).EQ.0)GO TO 392
      IF(MATRX3(J,2).NE.IZ)GO TO 392
      IF(MATRX3(J,3).NE.JZ)GO TO 392
      PTR=J
      GO TO 351
392   CONTINUE
C     PICK A TARGET REGION RANDOMLY
382   JX=INT(RANF(0.0)*30)
      IF(JX.GT.24)GO TO 382
      IF(JX.EQ.0)GO TO 382
      IF(MATRX3(JX,1).EQ.0)GO TO 382
      PTR=JX
C     IS FOVEAL FEATURE LIST EMPTY ?
351   IF(FFL.EQ.1)ANA=0
      IF(FFL.EQ.1)GO TO 353
      BLIND=0
C     CREATE NEW ANALYZER
```

```
        IF(HFN.GT.120)GO TO 353
        MATRX21(HFN,1)=FFL
        MATRX21(HFN,2)=PTR
        ANA=HFN
        HFN=HFN+1
        DO 370 J=8,20
        IF(MATRX20(J,FFL).GT.0)GO TO 370
        MATRX20(J,FFL)=ANA
        GO TO 353
370     CONTINUE
C       SET PREDICTION LIST TO ZERO
353     DO 352 J=1,16
352     PRED(J)=0
C       EXECUTE SACCADE TO FIXATE PERIPHERAL TARGET
C       REGION
350     KAC=0
        MAC=0
        IY=MATRX3(PTR,2)
        JY=MATRX3(PTR,3)
        IF(IY.EQ.0)GO TO 394
        KAC=MATRX15(IY,2)
394     IF(JY.EQ.0)GO TO 396
        MAC+MATRX15(JY,2)
396     KA=KA+KAC
        MA=MA+MAC
        IF(KA.LT.1)KA=1
        IF(MA.LT.1)MA=1
        IF(KA.GT.120)KA=120
        IF(MA.GT.120)MA=120
C       RESET VARIABLES FOR NEXT FIXATION
        PAN=ANA
        MATRX25(9,MOVE)=ANA
```

```
      MATRX25(10,MOVE)=FFL
      MATRX25(11,MOVE)=PTR
      MATRX25(12,MOVE)=DISCIN
      INMO=25-PTR
      ANA=0
      PTR=0
      GO TO 134
C     BLIND MOVE REFLEX - EXECUTE MOVE
360   DO 362 J=1,16
362   PRED(J)=0
      IF(SCAN.GT.1)SCAN=0
      IF(KA.LT.60)GO TO  368
      IF(MA.LT.60)GO TO 372
      IF(SCAN.EQ.0)KA=25
      IF(SCAN.EQ.0)PTR=51
      IF(SCAN.EQ.1)MA=25
      IF(SCAN.EQ.1)PTR=52
      GO TO 374
368   IF(MA.LT.60)GO TO 376
      IF(SCAN.EQ.0)MA=25
      IF(SCAN.EQ.0)PTR=53
      IF(SCAN.EQ.1)KA=85
      IF(SCAN.EQ.1)PTR=54
      GO TO 374
372   IF(SCAN.EQ.0)MA=85
      IF(SCAN.EQ.0)PTR=55
      IF(SCAN.EQ.1)KA=25
      IF(SCAN.EQ.1)PTR=56
      GO TO 374
376   IF(SCAN.EQ.0)KA=85
      IF(SCAN.EQ.0)PTR=57
      IF(SCAN.EQ.1)MA=85
      IF(SCAN.EQ.1)PTR=58
```

```
374   MATRX25(9,MOVE)=ANA
      MATRX25(10,MOVE)=FFL
      MATRX25(11,MOVE)=PTR
      MATRX25(12,MOVE)=DISCIN
      PAN=0
      ANA=0
      BLIND=1
      PTR=0
      INMO=0
C     RESET POINTER TO CENTRE OF DISCREPANCY INDEX
      DISCIN=(HITHR-LOTHR)/2
      GO TO 134
C     INPUT/OUTPUT FORMAT
120   FORMAT(213)
126   FORMAT(513)
121   FORMAT(13)
132   FORMAT(1H1)
123   FORMAT(//)
149   FORMAT(1X,'NO.',2X,30I4)
141   FORMAT(1X,'COL',2X,30I4)
150   FORMAT(1X,'ROW',2X,30I4)
143   FORMAT(1X,'PRE',2X,30I4)
144   FORMAT(IX,'ANA',2X,30I4)
145   FORMAT(1X,'FFL',2X,30I4)
146   FORMAT(1X,'PTR',2X,30I4)
147   FORMAT(1X,'DIS',2X,30I4)
148   FORMAT(1X,'MOM',2X,30I4)
552   FORMAT(1X,3513)
591   FORMAT(1X,I3,18I3)
C     END OF RUN
C     PRINTOUT ARRAYS CONTAINING FEATURE LISTS
```

```
C       ANALYZERS AND PREDICTION LISTS.
160     PRINT 132
        PRINT 552,(II,II=1,35)
        DO 5837 J=1,20
5837    PRINT 552,(MATRX20(J,I),I=1,35)
        PRINT 123
        DO 5838 J=1,120
5838    PRINT 591,J,(MATRX21(J,I),I=1,18)
        STOP
        END
```

4. A sample input.

CYCLOPS reads in data from cards in 4 blocks, though there is no physical separation of one block from another. The first five cards contain the values of several variables, two values per card. The variables are as follows -

Card 1. IJI, ENOUGH.

IJI refers to the number of data cards to be read in the second block; ENOUGH is the total number of fixations which can be made during the run.

Card 2. KA, MA.

KA is the initial column location in the visual world of the top left-hand corner of the fovea. MA is the corresponding row position in the visual world. The values of each variable may vary from 1 to 109.

Card 3. LOTHR, HITHR.

LOTHR is the value of the lower end of the discrepancy index, HITHR is the value of the upper end.

Card 4. MTCH, MISMTCH.

MTCH is the amount by which the pointer is moved down the discrepancy index after a match; MISMTCH is the amount by which it is moved up after a mismatch. Although these have always been set at +1 in all experiments with CYCLOPS, the option is available to set them at a variety of values.

Card 5. NPRIN, DISCIN.

NPRIN refers to the number of lines of output which will be printed. Information about fixations is recorded for a series of 30 fixations and then printed out. NPRIN refers to the number of lines printed out every 30 fixations. In the program listing, the fixation information which is recorded occupies 13 rows in MATRX25, so NPRIN is set to 13 to obtain a printout of each row. DISCIN is the initial position of the pointer on the discrepancy index. Depending on the size of the index, DISCIN is set to the mid point.

Each variable consists of a 3 digit number and there are 2 variables per card. The first is punched in columns 1 to 3; the second in columns 4 to 6, so the two numbers run consecutively. A sample set of cards is shown below -

003030	IJI, ENOUGH
082076	KA, MA
000006	LOTHR, HITHR
001001	MTCH, MISMTCH
013003	NPRIN, DISCIN

The second block of cards contains information about the patterns which are inserted into the visual world during a run. Each card contains 5, 3-digit numbers punched in columns 1 to 15. The first number (cols. 1-3) indicates at which fixation a pattern is to be inserted or deleted. These changes are carried out before subsequent visual processing proceeds. The second number (Cols. 4-6) indicates whether the pattern is to be added or deleted from the visual world, 000 = added, 001 = deleted. The third and fourth numbers (cols. 7-9 and 10-12) give the row and column positions in the visual world of the top left-hand corner of MATRX28 in which the pattern is copied. The final number (cols. 13-15) is a code for the pattern itself. The total number of cards in this block must be equal to IJI which was read in previously.

Patterns are stored in the pattern library section of the program as sets of instructions for creating patterns, rather than arrays of 1 and 0. The correct pattern is accessed by reading the code number (punched in columns 13-15). A conditional transfer, conditional on this code number, directs the control to the appropriate section of program in which the pattern instructions are located. These transfer statements can be found in the program listing immediately before the PATTERN LIBRARY, and are of the form IF(INE.EQ.N)GO TO M, where N is the code number which is read as data, and M is the statement number at the beginning of the corresponding set of pattern instructions. If additions were to be made to the pattern library, it should be noted that patterns are set up in MATRX28, and each set of pattern instructions is terminated by the unconditional transfer, GO TO 1106. Three examples of patterns are given in the listing.

A sample set of 3 pattern data cards is given below -

A 001000021045002

B 015001021045002

C 015000031060003

These cards will cause the following pattern entries and deletions. Card A instructs the program to enter pattern 002, starting at row 021 and column 045 of the visual world at fixation 001 of the series. Card B instructs the program to delete pattern 002, starting at row 021 and column 045 of the visual world at fixation 015. Card C instructs the program to enter pattern 003, starting at row 031 and column 060, and this is also done at fixation 015. Thus to substitute a pattern at any stage in the total series of fixations, 2 cards are required. The first deletes any existing pattern, and the second enters the new pattern. There are no restrictions on the number of patterns which may be entered or deleted at any stage, though a maximum of 70 data cards is allowed in this block. This is not a rigidly determined number, but depends on the size of the array into which the data cards are read (MATRX29 is (70,5)).

The third block of data cards is the same for every run, and consists of 24 cards, each containing two 3-digit numbers punched in columns 1 to 3 and 4 to 6. These cards contain information used by the saccadic reflex computation, and are read into rows 2 and 3 of MATRX3. Each of these numbers (except 000) addresses a row of MATRX15. There are 8 rows in MATRX15, each referring to different locations of a peripheral target region, ie. left, right, up, down, all at a distance of 24 units from the fovea, and left, right, up, down, all at a distance of 12 units from the fovea.

When the numbers of active peripheral regions in these four directions and two distances is computed, the totals are recorded in the first column of MATRX15. The 24 cards in this block are as follows -

1. 001003
2. 001007
3. 001000
4. 001008
5. 001004
6. 005003
7. 005007
8. 005000
9. 005008
10. 005004

11.	000003
12.	000007
13.	000008
14.	000004
15.	006003
16.	006007
17.	006000
18.	006008
19.	006004
20.	002003
21.	002007
22.	002000
23.	002008
24.	002004

Each of these cards refers to one peripheral region, for example, card 1 refers to region 1 in figure 22a. This region is situated LEFT of the fovea at 24 units, and UP from the fovea at 24 units. The corresponding rows for these directions and positions in MATRX15 are row 1 and row 3, and these are the numbers read in from card 1. In the computation of a peripheral target region, if region 1 was active (state = 1), the cells (row 1, col. 1) and (row 3, col. 1) would both be incremented +1 in MATRX15.

The final block of 8 cards contains information about the distances of peripheral target regions from the fovea, and is read into rows 1 to 8, column 2 of MATRX15. The information is punched as a 3-digit number in columns 1 to 3 of each card -

1. -24
2. 024
3. -24
4. 024
5. -12
6. 012
7. -12
8. 012

These final two blocks of cards for the saccadic reflex computation should be read in exactly as specified for each run.

5. Output.

Information about each fixation is recorded in MATRX25 and printed out every 30 fixations. Every line of printout is 125 characters in length. The first line (NO.) provides the number of the fixation in the total series, and not just the local block of 30 fixations. The second line (COL) records the column location in the visual world of the top left hand corner of the fovea, and the third line (ROW) records the row location.

Lines 4 to 8 (PRE) record the first 5 predicted analyzers for each fixation. The maximum number of predictions in a prediction list is 16, but for reasons of economy only 5 are printed. In all the reported simulations with CYCLOPS this number of entries in a prediction list was rarely exceeded.

Line 9 (ANA) contains the number of the analyzer matching the input at each fixation, and line 10 (FFL) contains the number of the foveal feature list, while line 11 (PTR) contains the number of the peripheral target region belonging to the analyzer. If no analyzer matches the input and none has been created (which happens if there is no input during a series of blind moves), the entry in line 9 is 0, while in line 10 it is 1 (indicating a blank fovea). In line 11 there will be a code number specifying the type of blind move which was made. If the moves started at the top left-hand quadrant and were in a clockwise direction, the successive codes are 57, 55, 51, and 53. If they started in the same position but were anti-clockwise, the codes will be 58, 54, 52, and 56.

Line 12 (DIS) records the position of the pointer along the discrepancy index, and the final line 13 (MOM) indicates whether there was a match (1) or a mismatch (0).

At the end of a run, the two arrays MATRX20 and MATRX21 are printed out. MATRX20 records the foveal feature lists and the analyzer numbers of which each list is a component and MATRX21 records the analyzers and their prediction lists.

APPENDIX 2

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