ON SYMMETRY IN VISUAL PERCEPTION

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ABSTRACT

This thesis is concerned with the role of symmetry in low-level image segmentation. Early detection of local image properties that could indicate the presence of an object would be useful in segmentation, and it is proposed here that approximate bilateral symmetry, which is common to many natural and man made objects, is a candidate local property. To be useful in low-level image segmentation the representation of symmetry must be relatively robust to noise interference, and the symmetry must be detectable without prior knowledge of the location and orientation of the pattern axis.

The experiments reported here investigated whether bilateral symmetry can be detected with and without knowledge of the axis of symmetry, in several different types of pattern. The pattern properties found to aid symmetry detection in random dot patterns were the presence of compound features, formed from locally dense clusters of dots, and contrast uniformity across the axis.

In the second group of experiments, stimuli were designed to enhance the features found to be important for global symmetry detection. The pattern elements were enlarged, and grey level was varied between matched pairs, thereby making each pair distinctive. Symmetry detection was found to be robust to variation in the size of matched elements, but was disrupted by contrast variation within pairs. It was concluded that the global pattern structure is contained in the parallelism between extended, cross axis regions of uniform contrast.

In the third group of experiments, detection performance was found to improve when the parallel structure was strengthened by the presence of matched strings, rather than pairs of elements.

It is argued that elongation, parallelism, and approximate alignment between pattern constituents are visual properties that are both presegmentally detectable, and sufficient for the representation of global symmetric structure. A simple computational property of these patterns is described.

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Anyone who visits the CCCN would be mistaken in thinking it is just an ordinary psychology laboratory. It's a magical place where the work is forgotten when a rainbow appears, where people eat toadstool sandwiches for lunch, where people fly on stormy days, where colours are heard and sounds are seen, and where music tastes like chocolate cake. If you listen carefully at night you can hear country and western ballads echoing in the corridors, and from time to time the biscuit fairy has even been known to visit. Visitors beware, sometimes people who come here never, ever leave again........

This work is dedicated to Mary and Pat Boyle.

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INTRODUCTION

Many experiments in symmetry perception are based on the premise that bilateral symmetry is a special or particularly salient structure for which there exists a dedicated processing mechanism. The supposition that a such a mechanism exists was explicitly stated in early studies (Bruce and Morgan, 1975; Corballis and Roldan, 1974) and was thought to be supported by evidence that bilateral symmetry is processed more easily and more rapidly than other similar pattern types such as repetition and other symmetries. For example, Bruce and Morgan proposed that bilateral symmetry perception may involve a global process which detects the pattern as a whole, whilst the perception of repetition might involve a serial matching of individual pattern elements. The fact that a distinction is drawn between bilateral symmetry and similar pattern structures, such as repetition, indicates that the postulated detection mechanism is highly specific to bilateral symmetry and does not detect other pattern types. One consequence of this is a tendency in the literature to focus on a very narrow working definition of symmetry, as described by reflection of a pattern about an axis, where each point in the pattern is matched by an identical point at the same distance, on the opposite side of the axis. Research in symmetry perception is heavily focused on this narrow definition of perfect bilateral symmetry, yet it would be surprising if a symmetry detection mechanism had evolved in the visual system to process precisely this pattern structure, as it is very rarely observed in natural settings. It is argued in this thesis that there may be a number of mechanisms involved in symmetry perception which are useful for different visual tasks. There is a tendency in the literature to look for a single mechanism for symmetry detection, with no broad agreement about what such a mechanism would be used for and this may be part of the reason why no single, unifying theory of symmetry perception has been found. In light of this, the role of symmetry perception is considered here in relation to the specific task of image segmentation.

1.1 Overview of Chapter 1

The work of this chapter begins with an introduction to some of the early theories of symmetry perception and the sorts of processes thought to be performed as part of this process. There then follows a discussion of Barlow and Reeves (1979) broad study on symmetry perception which introduced many of the issues that are still currently of interest in the field. In Section 1.2.3, it is proposed that the choice of stimulus pattern and task in symmetry experiments may have greater influence on subjects performance (and thereby on models and theories of symmetry perception) than has been previously acknowledged. This proposal is illustrated through an examination of the studies conducted on the effects of axis orientation on symmetry perception. It is argued that the apparent incoherence in the results of these experiments, and the failure to identify a mechanism for symmetry detection is due to two things; the lack of adequate experimental controls between the experiments, and the existence of not one, but possibly many, task dependent, mechanisms for symmetry detection. Some of the factors influencing symmetry detection emerge from this discussion, and these are presented in Section 1.4, although this section is probably not exhaustive. These factors are considered in light of some proposals for the operation of more general visual processes in symmetry perception, which are not specific to perfect bilateral symmetry, but which detect the characteristic emergent features of symmetry-like structures (i.e., local orientational uniformity). The usefulness of this general approach is discussed in relation to a recent model of symmetry perception which involves the computation of specific relations between elements.

1.2 A review of studies on symmetry perception

1.2.1 Early models of symmetry perception

It is recognised that symmetry perception may involve processing at different levels. Julesz (1971) observed that symmetry in 'complex' or high frequency patterns is detectable only when the axis is fixated, whilst 'simple' symmetric forms are detectable in the visual periphery. Julesz proposed that symmetry at fixation may be mapped directly on to symmetrically positioned loci in each cortical hemisphere and that detection occurs via some point-by-point matching process between these points. However, Julesz did not specify a mechanism for detecting symmetry projected extra-peripherally, or for directing attention to the axis region of a pattern.

Similarly, Bruce and Morgan (1975) and Palmer and Hemenway (1978) proposed a two stage process in symmetry perception. The first stage involves an initial global analysis of the stimulus which is coarse and rapid and serves to establish global pattern characteristics such as pattern type or axis orientation and is followed by a second stage of more deliberate scanning around the selected axis. However, relatively little consideration was given to the details of the initial crude stage of processing. One reason for this may be that the experiments were heavily oriented towards the second scanning stage of processing, as testified by the use of reaction times which fluctuated around 3 seconds in both the Bruce and Morgan and the Palmer and Hemenway experiments. In the Bruce and Morgan experiment the task was not to detect symmetry but to detect a small violation of symmetry and in Palmer and Hemenway's experiment subjects were required to discriminate between 'perfectly symmetric' and 'nearly symmetric' polygons. In both of the studies cited the symmetric targets were presented on a noise free background in a centrally fixated position with respect to the subject. These tasks did not require the symmetry to be located or segmented from the background. Moreover, in both of these studies, the nature of the tasks required that subjects make negative responses to highly regular stimuli.

Thus, these early models of symmetry perception alluded to the need for a global stage in symmetry detection, but were focused on the more local processes presumed to occur after the global information is obtained.

1.2.2 The flexibility of symmetry detection mechanisms

The series of experiments reported by Barlow and Reeves (1979) is one of the most influential in the field of symmetry perception, and one of the first to consider the capabilities of global and local symmetry detection mechanisms. In the first of these experiments which investigated sensitivity to symmetry in a background of noise, Barlow and Reeves determined observers ability to discriminate two populations of random dots, where one of these (the target stimulus) contained a proportion of symmetrically paired elements. They found that perfectly symmetric patterns were perfectly discriminated from unstructured noise. In the presence of uncorrelated noise dots which diluted the symmetric signal, discriminability between the two stimuli declined gradually as the proportion of symmetric element pairs was reduced in the target stimulus. Barlow and Reeves concluded that symmetry is not a binary feature to the visual system, but instead is represented internally as a graded quality and that the degree, or 'amount' of perceived symmetry in a pattern varies continuously with signal to noise ratio. One practical implication of this finding is that the degree of symmetry in a pattern can be determined by the signal to noise ratio in the stimulus and can be manipulated as a real experimental variable. Thus, although symmetry detection may be a complex pattern recognition task which is not fully understood, the strength of the symmetric signal can be determined by the relatively simple measure of signal to noise ratio. This continuous quality allows signal detection methods to be used in experimentation.

The finding that subjects respond to noise dilution of symmetry in a graded rather than a discrete manner also has a further, more theoretical implication for studies of symmetry processing. The graded response suggests that the visual system is able to detect structure or pattern which is imperfectly or approximately symmetric. Such pattern is not adequately described by the precise, mathematical definition of symmetry, however it is nonetheless represented by the visual system as evidenced by the consistent, graded patterns of response found by Barlow and Reeves. It is probably useful to distinguish between the externally determined description of perfect bilateral symmetry and the internal representation of symmetric structure which will be termed 'visual symmetry'.

A model of symmetry perception is required which satisfactorily accounts for the global, flexible stage of symmetry detection. Further experimentation by Barlow and Reeves (1979) specified some other requirements for such a model. They discovered that although subjects were able to detect noisy or disrupted symmetry, they could also detect relatively small amounts of noise on a symmetric pattern. This suggests that the visual system can be both sensitive and insensitive to disruption of symmetry, depending on task demands. Barlow and Reeves also measured subjects ability to detect distorted symmetries using patterns in which the distortion was created by adding some positional noise to the relative positions of paired dots. In this task performance was found to fall gradually as the amount of displacement increased. Furthermore they found that symmetry detection is not dependent on fixation upon the axis, although there is a detection advantage when the axis position is known. The importance of information in the axis region was confirmed by the finding that the element pairs in the axis region of a symmetric pattern was found to contribute more to the detection of symmetry than those in more distant positions. Subjects were able to detect symmetry at all axis orientations, although superior performance was found at vertical and horizontal orientations than those in between.

The overall conclusion from this pattern of results is that symmetry is a highly salient pattern structure which is detectable without close scrutiny or deliberate point matching of symmetric elements even under conditions of noise disruption and moderate pattern distortion. However, this does not indicate that the visual system is simply insensitive to disruption of symmetry, as Barlow and Reeves results also indicate that small amounts of noise are easily detected in symmetric patterns. These findings give an indication of the level of flexibility required in any proposed symmetry detection mechanism. Barlow and Reeves postulated a coarse scale detection mechanism which calculates a coarse, cross axis correlation in order to detect symmetric or approximately symmetric relations between local clusters of dots. Such a model is able to account for the gradual decline in subjects performance under conditions of noise dilution or pattern smearing, but not for the effects of axis positional uncertainty or orientation, as the position and orientation of the axis must be determined prior to making a cross axis comparison. Barlow and Reeves also note that the correlation model does not account for the greater importance of elements close to the axis, but that this could be corrected by some adjustment to the model such that more accurate measurements are made in the regions closest to the axis.

Despite the drawbacks of the correlation model, the importance of this contribution was to propose the existence of a mechanism for symmetry detection which depends neither on a deliberate scanning of patterns to find symmetric matches, nor on perfect bilateral symmetry, but a coarse scale mechanism which could be used to group elements into a coherent structure using some sort of approximation to symmetry. This study highlighted the fact that pattern form other than the pairwise symmetry relationship between dots may be used in the perception of symmetric structure.

1.2.3 Random dot patterns in symmetry research

Following Barlow and Reeves (1979), the vast majority of research on symmetry perception has employed the random dot pattern as a vehicle for studying symmetric structure and these have the advantage of allowing structure to be studied in abstract, separating high-level effects of familiarity and recognition from those of lower level pattern perception. However, there is a strong implicit assumption in using random dot stimuli that the essential perceptual aspects of symmetric structure can be reduced to one type of pattern (i.e., that there is only one type of symmetric structure) and that this is isolated and contained in the reflection of points about the axis. It follows from this that a single mechanism is also assumed, operating at the level of the individual reflected pairs. These assumptions are not always stated explicitly, but are evident in the fact that the reflection of points is often the only structure deliberately built in to the symmetric dot patterns. As a consequence, very little attention has been given to the global structure present in random dot stimuli.

However, even in random dot patterns which purportedly present symmetry in abstract, the perceptual content of the patterns may be changed by stimulus parameters such as the number, size or distribution of elements in the display (Julesz, 1971). These factors tend to be selected arbitrarily by experimenters, therefore it is possible that random dot patterns may contain certain properties which are not properly controlled between experiments. Without knowing what kinds of pattern form are perceptually important, which stimulus factors affect the pattern form, and how the importance of different pattern form varies with task, we cannot be certain of the visual significance of the patterns typically used in symmetry experiments.

One result of uncontrolled pattern content is that apparently similar experiments may be fundamentally different at the perceptual level. Where this happens the experiments may yield different patterns of results which will appear incoherent because they are not explicable within the single mechanism paradigm. Alternatively, results which appear similar will simply be interpreted within the single mechanism paradigm and will disguise the underlying differences between stimuli and tasks used. Either of these generalisations will obscure the mechanisms used to detect the symmetry in each task.

A further possible source of confusion in the literature is added by the variety of tasks presented to subjects. It is possible that where a single detection mechanism is assumed, the effects of task type are ignored, given that the same mechanism should operate in all tasks. Again, this is not stated explicitly, but is evident in manner in which results from very different task types are compared. Again, until we know whether task demands alter the perceptual requirements of the task, the failure to control for task type may add unnecessary confusion to the results.

These points are best illustrated in the literature on orientational effects on symmetry detection.

1.2.4 Symmetry and orientation

The purpose of studying the effect of any stimulus parameter on performance in symmetry tasks is to construct, or to contribute, to a model of symmetry perception, based on some consistent effect of that parameter. If it is assumed that a single mechanism exists that is both specialised for symmetry and sufficiently flexible to detect a wide variety of instances of symmetry, it should follow that a single pattern of detectability will be found and no interactions between the global transformation of orientation and local pattern factors will be expected.

One major problem for the single mechanism hypothesis in symmetry perception is that a consistent effect of orientation has not been found, therefore orientational effects on symmetry perception cannot be accounted for by any single model. Wagemans et al. (1992) note that 'every possible ordering of the detectability of symmetry about different axes' can be found in the literature. These varying patterns of detectability have given rise to a variety of competing models of symmetry perception and hence to considerable confusion in the literature about the effects of orientation in symmetry perception.

1.2.5 Proposed theories of symmetry detection

The most commonly found pattern of detectability is that vertical axes are most rapidly and easily detected, followed by horizontal and then diagonal axes (Barlow and Reeves, 1979; Palmer and Hemenway, 1978; Wenderoth, 1994, Experiment 1). This ordering is written as V>H>D, where the symbol '>' is taken to mean 'is more easily detected than' and '=' denotes 'is as easily detected as'. Some instances of alternative patterns of preference are: V>D>H (Corballis and Roldan 1975), V>H=D (Pashler, 1990), V=H=D (Locher and Wagemans 1993), D>V=H (Wenderoth 1994, Experiment 2) and H>V (Jenkins, 1983b), V=H>D (Fisher and Bornstein, 1982).

However, the patterns of preference for different axis orientations give little insight into what the mechanisms involved in symmetry detection might be. Even within one ordering, there is no consensus about how the pattern of results should be interpreted, and any single pattern of preference may be equally explained by both very low level and very high-level accounts.

For example, there are a variety of interpretations of the most frequently observed ordering of V>H>D. One possibility is that this pattern reveals a finely tuned low level bias towards the cardinal axes. This bias has been observed in a range of orientation tasks involving distributed attention and is termed the oblique effect. A variety of explanations have been offered to account for the oblique effect. One possibility is that obliquely oriented visual filters are more noisy than those at the major axes (Rubenstein and Sagi, 1990). Atkinson (1972) and Jenkins (1985) suggest that the effect may be due to nonuniformity in the size and shape of visual filters at different orientations, possibly due to a bias in the visual diet (Annis and Frost, 1973). Foster and Ward (1991) suggest that the oblique effect is compatible with the patterns of detectability expected from horizontal and vertical filters operating in early vision, whilst Treisman and Gormican (1988) propose that coding processes may be more complicated for stimuli at non-cardinal orientations.

In contrast, Wenderoth (1994) rejects wholly low level accounts of the V>H>D pattern of detectability. He reports that detection performance is better precisely on the diagonal than at the orientations immediately surrounding it. This subtlety is often overlooked because most studies test only the effects of the major axes, and the results contradict the oblique effect which predicts that the worst performance should occur directly on the diagonal as this is the furthest point from the cardinal axes.

Wenderoth also reports that the detectability of symmetric patterns is influenced by the range of axis orientations presented to the subject. He argues from this evidence that orientational preferences are malleable rather than fixed, and that symmetry detection is influenced by attention.

Another possible explanation for the V>H>D order of detectability is that humans have a normal horizontal and vertical perceptual reference frame which causes an attentional bias (Pashler, 1990). Alternatively, it has been suggested that observers attend selectively to the cardinal axes simply because these are more easily monitored than diagonals (Wenderoth, 1994).

Palmer and Hemenway propose yet another explanation which involves a sequential selection and evaluation of axes, in which the order of testing is not strictly fixed, but biased towards the cardinals. Thus the order V>H>D is determined probabilistically rather than by a strict sequence of testing.

The above explanations have been proposed for only one order of detectability. There are other accounts offered to explain the other patterns of detectability. Corballis and Roldan (1975) report an orientation function (V>D>H) that shows an increase in detection latency with angular distance from the vertical. This, they claim, supports a mental rotation model, in which the pattern axes are mentally rotated towards a vertical norm. However, it is doubtful whether the mental rotation hypothesis provides an adequate account of symmetry detection, as logically, detection of the pattern must occur prior to rotation. Thus, the initial detection mechanism is unexplained and the rotation effectively redundant. The displays used in the Corballis and Roldan experiment included explicitly drawn midline axes, providing a highly salient cue to the pattern orientation which could feasibly be used to solve the task independently of any global pattern detection. Moreover, Corballis and Roldan tested only the four main axes and no intermediate ones, therefore there is no way to determine whether latencies increase smoothly with orientation, (as predicted by the mental rotation hypothesis), or whether the orientation function changes abruptly at the major axes. The latter pattern does not support the mental rotation hypothesis.

Jenkins (1985) finds that observers are most sensitive to horizontal patterns and proposes that this effect is due to receptive field size which is largest in the vertical orientation, followed by vertical and then oblique.

Fisher and Bornstein (1982) report that observers are equally sensitive to vertical and horizontal patterns. However, they argue that learning effects must be taken into account as the subjects increasing familiarity with the limited range of stimuli and orientations tested (4 main axes) may serve to reduce what is initially a vertical advantage.

It is clear that we can tell very little about mechanisms for symmetry detection from orientational effects alone. A single mechanism which is sufficiently flexible to detect symmetry under a range of stimulus conditions would be expected to produce a single, consistent pattern of results between experiments. The fact that no single ordering of detectability has been identified suggests that one single mechanism cannot be responsible for all aspects of symmetry perception. However, the patterns of detectability found in these experiments do not directly reveal the possible mechanisms in symmetry detection, as each pattern of results is potentially explained by several different mechanisms. Thus, there is disagreement not only in the patterns of results obtained, but also in how any single pattern should be interpreted.

1.3 Reconsidering the evidence

The apparent confusion in the literature has arisen because the majority of studies on orientational effects are concerned only with the effect of the global orientation transformation. As a consequence of this, experiments concerning orientation effects largely disregard the possible effects of interactions between global and local pattern factors and the possible effect of task. If on the other hand we assume that local pattern factors and task demands alter the perceptual requirements of the task, patterns of detectability might well be expected to vary between experiments, as different the perceptual tasks presented by a range of stimulus conditions may invoke a variety of detection mechanisms.

For example, amongst those studies cited which obtained the most common ordering of V>H>D, the stimuli and tasks differed markedly. Palmer and Hemenway used polygon outline stimuli whilst both Barlow and Reeves and Wenderoth used dot patterns. The two types of dot pattern used were different; those used by Wenderoth were more uniformly distributed than those used by Barlow and Reeves, the stimulus field was increased for the purpose of removing outline cues, dot size was increased, and dot separation was set to a minimum of two dots diameter.

Exposure times were also different in the three studies: 100 ms in Barlow and Reeves, 2 seconds in Wenderoth, and unlimited in Palmer and Hemenway.

The experimental tasks also varied. In the Palmer and Hemenway task the distractors contained some regular spatial structure (they were either 'nearly' symmetric or rotationally symmetric), whilst the other two required the subjects to discriminate symmetric patterns from random dot distributions. In the Barlow and Reeves task however, the target stimuli contained 20% uncorrelated dots. Barlow and Reeves tested at the four main axes in blocks of trials for each orientation, Palmer and Hemenway tested the four main axes at random, whilst Wenderoth (Experiment 1) tested eighteen orientations randomly.

Clearly, there are many inconsistencies between these three studies and until the effects of, and interactions between the different stimulus and task factors are known, we cannot be certain whether the consistent pattern of detectability found in these results is only a superficial similarity, or whether they are in fact due to a strong overall effect of axis orientation.

A similar lack of consistency in experimental and task factors is evident in those studies which found other patterns of detectability. The task used by Corballis and Roldan (1975) did not require a discrimination between symmetric and random patterns, but rather a discrimination between symmetry and repetition in very regular block type patterns. The 4 major axes were tested both randomly and in blocks; however the axis was explicitly drawn on these stimuli thereby directly cueing the orientation on all trials. Exposure duration was relatively long at 2 seconds. In contrast, the task in the Jenkins (1983b) experiment was not the detection of perfect bilateral symmetry, but rather, orientational uniformity of point pairs. These stimuli were comprised of dynamic point textures presented for 1 second and the distractor stimuli were random textures.

What should be clear from these descriptions is that studies which do find consistent effects of orientation show as much variability in stimulus and task factors as studies which differ in results. Moreover, the nature of the interactions between orientational and other stimulus and task factors are opaque because the tasks are not directly comparable, therefore it is of little use to try to infer a gross effect of axis orientation or a possible mechanism for symmetry detection on the basis of these studies.

However, the lack of a single, clear effect of axis orientation is problematic only if the stimuli and tasks used in the experiments are believed to be essentially similar and if a single mechanism for symmetry perception is sought. An alternative approach to this body of literature is consider that a number of mechanisms may be used in symmetry perception, and that these may be affected by stimulus and task factors other than orientation. As noted, if this was the case, then consistent patterns of detectability might not be expected between experiments which vary so widely in these factors.

1.4 Factors affecting symmetry perception

Some of the potentially important contributory factors can be identified in the symmetry studies although the relative contributions of these are difficult to gauge given the widely ranging evidence presented in these studies and the variations in the stimuli used. The experimental factors identified as potentially important are those concerning the observers prior knowledge of the stimulus content and the experimental task type. The stimulus factors identified are element type and element distribution.

1.4.1 Prior knowledge of axis orientation

There are a number of factors present in these tasks which may be interacting. One of the factors which may affect performance is the presence or absence of orientation cues which may be given either explicitly by a fixation line (Pashler, 1990) or a drawn axis line (Corballis and Roldan, 1975) or, more implicitly by the blocking of trials by orientation (Corballis and Roldan, 1975; Wagemans et al., 1992; Locher and Wagemans, 1993) or biasing the distribution of orientations (Wenderoth, 1994).

Effects of cueing axis orientation are used to probe the issue of whether it is possible to mentally prepare for an axis of a particular orientation, however the results are inconclusive. Both Corballis and Roldan (1975) and Locher and Wagemans (1993) found that blocking trials by orientation (thereby implicitly cueing orientation) did not alter the order of detectability found in randomised trials and concluded from this result that it is not possible to prepare in advance for a particular axis orientation.

A detection advantage for cueing has been taken to indicate that axes can be anticipated and an advantage for cueing was reported by Wenderoth (1994), who found both reduced errors and reaction times and an alteration in the pattern of detectability as a result of biasing the distribution of orientations tested. Wagemans et al. (1992) found that the effect of blocking by axis orientation on the detection of bilateral symmetry was to considerably reduce both reaction times and errors. In these studies, the symmetry was detectable in both the blocked and unblocked conditions and no changes were observed in order of detectability (V>H>D).

Where cueing is seen to improve performance however, there is no way to determine whether cueing simply causes increased speed and accuracy in performance, or whether detection mechanisms are different in cued and uncued conditions. The lack of a cueing effect may not simply indicate that attention, or the directing of attention fails to occur, because it cannot be assumed that explicit attention is necessarily required in symmetry detection. Whilst a result which shows no advantage for cueing might indicate that attention cannot be directed to the axis, it might equally indicate that the pattern is detected by a low level, preattentional mechanism. No advantage (or a lesser advantage) for cueing should be expected for stimulus patterns that can be detected globally.

Thus, in order to tease out the different mechanisms that may be used in symmetry detection, it is first necessary to identify patterns of performance which clearly indicate the use of different strategies (i.e., global and local) to detect the same pattern under known and unknown axis orientations, or instances where cueing allows patterns to be detected which cannot be detected when uncued. It may then be possible to identify the stimulus factors and pattern characteristics which are associated with the different strategies.

Locher and Wagemans (1993) carried out a detailed study of this sort, investigating the effects of orientation element type, axis information and grouping on symmetry detection. They found no overall effect of blocking across a range of element and pattern types (e.g., grouped and ungrouped, single and double axes) but note that orientation information may be less useful in patterns where the spatial properties of the pattern make global symmetry highly salient. Interactions between effects of cueing and pattern form apparently require further investigation.

1.4.2 Prior knowledge of axis position

In many studies in symmetry perception, the stimuli are presented in a fixed position with respect to the observer. The effect of axis positional knowledge is often overlooked, but may have some bearing on the mechanisms used in symmetry detection. Axis knowledge may provide a cognitive basis for a discrimination task, as the pattern itself does not have to be located and the detection of symmetric pairings can be carried out by deliberate matching of points about the axis. In such a case it would be very local information rather than the global symmetric pattern providing the basis for discrimination. It should be noted that the use of a local strategy does not necessarily imply the use of deliberate scanning. Julsez found that random dot symmetry was detectable at 50ms exposure durations, provided the axis position was known to the subject. At this short exposure time, deliberate scanning or point matching strategies are eliminated, therefore it must be concluded that symmetry can be detected by a mechanism which is not attentional, but is nonetheless local.

Although the effects of cueing and blocking axes are frequently used to investigate issues of focal and global attention in symmetry detection tasks, the use of random axis orientation fails to fully dissociate global and local mechanisms. Where the axis position is known to the subject an attentional strategy may still be used by the subject despite orientational uncertainty, as a fixed axis position provides a focal point about which to test, and the range of possible orientations is often restricted to as few as four (Corballis and Roldan, 1975;

Palmer and Hemenway, 1978). However, where both orientation and position are unknown, the range of possible axes is unlimited and no systematic testing strategy is available.

Foster and Ward (1991) note that the oblique effect (i.e., the superior detection at the cardinal axes) tends to be observed in tasks involving distributed attention, whilst focal attention (permitted by a centrally fixed axis and long exposure durations) reduces the oblique effect, yielding a more continuous distribution of detectability. It might be expected therefore that an oblique effect should be observed under both positional and orientational uncertainty, however there is insufficient data to support so specific a prediction. Nonetheless, the data does suggest that symmetry detection and the effects of orientation are dependent on position information.

Pashler (1990) found that where axis position was known to the subject (i.e., centrally fixed), orientation cues produced an improvement in detection performance. Where the position of the pattern was not known, orientation cues produced no advantage, although the symmetry could still be detected. Wenderoth (pers comm) found subjects were unable to perceive any symmetric structure under both positional and orientational uncertainty. The difference in overall detectability of random dot symmetry in the two experiments, under conditions of uncertainty, suggests that symmetry detection depends on some other task and stimulus factors.

1.4.3 Task type

It is perfectly possible that different psychophysical tasks place very different demands on the visual system, and therefore exploit different mechanisms. This should be taken into consideration when comparing results from studies which use different tasks. For example, in Barlow and Reeves (1979) first experiment, the task is to discriminate symmetric patterns with added noise from random patterns and requires only that the subjects detect some structural regularity. However, the Corballis and Roldan (1975) experiment required the subjects to discriminate between two highly structured stimuli (symmetric and repeated patterns). This task cannot be done on the basis of the detection of approximate structure or regularity, but requires that the precise relationships between the patterns elements be processed. This may be a cognitive rather than a purely perceptual task, and in light of this distinction, Corballis and Roldans (1975) mental rotation hypothesis which does not fully account for the initial detection of global structure becomes a plausible explanation of stimulus manipulation at higher levels of processing.

Other tasks (Rock and Leaman, 1963; Fisher and Fracasso, 1987) involve similarity judgements in which subjects decide whether a horizontal or a vertical pattern is most similar to a pattern symmetric about both axes. The purpose of this experiment was to establish which of the single axis patterns is most representative of the double axis pattern under conditions of head tilt at angles between the two orientations. However, in tasks involving similarity judgements, there is no way to determine the criteria used by the subjects. Preferences were found to vary according to the instructions given, and according to the age groups of the subjects tested, suggesting that the subjects understanding of the term 'similar' may be dependent on context and subject differences. Fisher and Fracasso also point out that stimulus characteristics other than axis orientation (e.g., pattern size, contour, and colour) may influence similarity judgements, particularly in young children.

Whilst it is not possible to determine the exact nature of the effect of task type on symmetry perception, some idea of the effect of task type may be gained from considering what is the least information that is required to do each task. Barlow and Reeves task could feasibly be carried out by a global mechanism, whilst the others will almost certainly require more specific, local pattern detail.

1.4.4 Element type

Many studies in symmetry perception use random dot patterns. The perception of symmetry in random dot patterns requires that relationships are detected between points which are neither adjacent, nor explicitly connected. Stimuli depicting only shape outlines have also been used in symmetry research but less commonly than dot patterns. These too are used to investigate the perception of structure in abstract but it is not clear that polygons are processed in the same way as dot patterns (Zucker, 1986). Polygon stimuli make explicit the shape information which in principle only becomes available in random dot patterns after lower level grouping has been carried out and the emergent relations have been detected. The dot matches which are made explicit in outline stimuli are those which are highly specific to the individual shape rather than those which are common to all symmetric patterns. The presentation of an explicit outline eliminates the requirement to detect emergent structure in the stimulus but instead may prompt a strategy in which the patterns are tested for bilateral equivalence by scanning around the outlines (Locher and Nodine, 1973; Freyd and Tversky, 1984).

Although dot patterns are most commonly used, the type of configurational element in the pattern has been found to have little or no effect on symmetry detection and patterns comprised of symmetrically positioned dots, blocks and line elements are in most cases equally well detected. Koeppl (1993) reported that detection performance was affected more by jitter on the relative positions of symmetrically matched line elements than by noise on the orientation of the elements. The absence of an effect of element type may suggest that component elements are coded as an integral part of the global stimulus and that symmetry relations between grouped elements are processed independently of particular element characteristics (Royer, 1981; Locher and Wagemans, 1993).

However, it may be argued that the absence of an effect alone makes no distinctions in the possible mechanisms involved in symmetry detection. Whilst this result is compatible with a coarse or global processing mechanism, it does not preclude the possibility that a local strategy is used, as there is no a priori reason to suppose that a local or attentional mechanism such as the deliberate matching of point about the axis would be in any way dependent on local element characteristics. In order to separate the two mechanisms it is necessary to identify element characteristics which do not disrupt a strategy of deliberate matching for symmetric positioning, but which do disrupt the pre-attentional detection of global symmetry. It is the exceptions to the general finding which may prove more useful in this enquiry.

One such exception is reported in Locher and Wagemans (1993) who found that symmetry could not be detected in patterns comprised of uniformly distributed elements of mixed orientation, where orientation was matched within, but varied between element pairs. A local mechanism, operating directly at the level of individual elements is by definition independent of surrounding information and therefore should be equally effective irrespective of the orientation of the other pairs. Subjects inability to detect symmetry in the mixed orientation patterns indicates that symmetry detection in this task is dependent not only on cross axis matching but also on the perception of particular spatial relations between element pairs. This suggests that local grouping is carried out prior to symmetry detection by a mechanism which is sensitive to local orientation.

Symmetry detection is also found to be disrupted by local contrast differences, particularly where the contrast of pairs is mixed such that the elements of each contrast sign are randomly allocated to each side of the axis (Zhang and Gerbino, 1992; Zhang, 1992). The perception of symmetric positioning at the level of dot pairs is unlikely to be disrupted by contrast differences.

These results do suggest that the global perception of symmetric structure is mediated by a grouping mechanism which precedes the detection of positional alignment across the axis and which is sensitive to both local orientation and local contrast.

It may be significant that the two stimuli which appear to disrupt grouping and global detection are both stimuli in which the constituent elements are non-identical. Notably, the mixed orientation stimulus was the only such example from both Royer and Locher and Wagemans experiments. The visual mechanisms which detect symmetry may be relatively insensitive to differences between distributions of small elements of uniform contrast, size and orientation. However, it is possible that symmetry detection and the mechanisms involved are not independent of element type as suggested, but instead that the absence of an effect of element type can be attributed to the relatively narrow range of element types tested.

1.4.5 Element distribution

Julesz (1971) proposed that certain pattern statistics may determine subjects ability to detect cross axis correlations; in particular that the formation of clusters in dot patterns may aid in the encoding of global spatial relations. He noted that in patterns with uniformly distributed line elements, symmetry was only apparent in those elements directly around the axis region whilst correlations between the more widely separated elements were not detected except by explicit and careful matching. However, in patterns with nonuniformly distributed elements, local clusters emerged which themselves formed larger scale 'tokens' that are matched at a global level. Locher and Wagemans (1993) also found that symmetry detection performance was greatly improved as a result of pregrouping the pattern elements by varying the local density of elements across the stimulus field. Other pattern factors, such as the introduction of additional elements close to the axis and even the number of symmetry axes were found to have relatively subtle effects in comparison to the effect of grouping. Labonte et al. (1995) also report a facilitating effect of grouping by orientation.

These findings are consistent with Barlow and Reeves (1979) suggestion that symmetry detection under certain conditions may operate at a coarse level on local element clusters rather than at the more accurate level of matching individual dot pairs.

1.4.6 Summary

What, if any, conclusion can be drawn from this body of research? Although no single pattern of preference can be found, it is evident that observers are efficient at detecting symmetry under a wide range of stimulus conditions. The evidence presented above suggests that a variety of mechanisms, rather than one single mechanism may be used in symmetry detection. Whilst it is feasible that a single mechanism might be sufficiently flexible that it could detect symmetry under a wide range of conditions, some consistency under broadly similar conditions (such as varying orientation) would nonetheless be expected. However, subjects patterns of performance vary greatly under such broadly similar conditions, depending on other experimental conditions. Thus, although humans ability to detect symmetry is found to be flexible, there is no strong evidence for a single detection mechanism in the body of literature reviewed above. Moreover, a dedicated symmetry detection mechanism would require the peculiar capability of detecting both perfect and approximate symmetry whilst failing to detect other, very similar and perfectly regular pattern such as repetition. Such a mechanism would need specific knowledge about reflection and also some criterion for accepting or rejecting imperfectly symmetric stimuli. Thus, although reflection is a unique pattern property which distinguishes symmetry from other pattern types, there is little reason to suppose that the detection of global symmetry involves any explicit knowledge of the reflected relationship between point pairs. The fact that symmetry can be detected despite noise and distortion and without deliberate scanning of matched pairs indicates that symmetry, (or at least some structural regularity) can be detected without any specific knowledge about the precise relationship between the elements and the axis. This suggests that the property of reflection is not in itself a visual feature and may be irrelevant, at least in the representation of global symmetry.

1.5 General purpose mechanisms for symmetry detection

An alternative approach to the study of symmetry perception is based on the premise that symmetry is not a special status pattern, but rather, a particularly salient member of a wider class of patterns to which the visual system is sensitive. The practical implication of this approach is that there is not then thought to be a dedicated symmetry detection mechanism, but instead, a more general mechanism for detecting structure.

In seeking a mechanism for symmetry detection, we must be clear about what it is that such a mechanism should detect. In other words, a new working definition of symmetry is required. Such a definition cannot simply describe the reflected structure, but must include a description of the emergent features and relationships which are precipitated by the reflection. This highlights the need for an investigation of symmetry perception which is not bound to the mathematical definition of symmetry or to the idea of a single symmetry detection mechanism, or even to the idea of symmetry as a single type of pattern. An alternative approach to the study of symmetry perception is to investigate the nature of 'visual symmetry' rather than perfect bilateral symmetry, in other words to determine what forms of symmetric pattern we can perceive, and the stimulus and viewing conditions necessary to perceive them. There is no agreed predefinition of visual symmetry and the intention of this approach is to construct such a definition through a series of appropriately controlled tasks and the known properties of visual mechanisms. Thus, the aim of this type of study is to arrive at a definition of visual symmetry which will also describe the nature of the internal representation of visual symmetry.

1.5.1 Spatial filtering operations and symmetry

Julesz and Chang (1979) observed that two symmetric noise patterns, superimposed at 90 degrees, yield no perceptible structure at either orientation. However, when spatially filtered at different bandwidths and superimposed, both symmetries became apparent with the coarse scale structure the more dominant of the two. Julesz and Chang proposed that symmetry detection may be preceded by spatial filtering operations which make global symmetry explicit at coarse scales.

Coarse scale spatial filters average luminance over local image regions. Local variance is averaged out and the gross luminance changes in the image are enhanced. The idea that spatial filtering operations may precede the attentional, point matching stage of symmetry perception is not a new one (see Royer, 1981; Jenkins, 1983b; Pashler, 1990; Locher and Wagemans, 1993; Dakin and Watt, 1995). Very little experimental work has been reported that directly tests the predictions of a filter model however, the observed perceptual effects of certain stimulus manipulations are compatible with spatial filter responses.

Spatial filters provide a mechanism which is sufficiently flexible and versatile to account for observers tolerance to noise and perturbation on the signal (Barlow and Reeves, 1979). Spatial filtering carried out in parallel across the visual field will reveal global structure at every position and orientation and may provide some means for orienting attentional mechanisms toward the axis. A model which uses coarse scale filtering prior to symmetry detection may thereby provide a more complete explanation of Barlow and Reeves experimental findings than their proposed autocorrelation model which requires that the position and orientation of the pattern axis are known in advance. Similarly, coarse scale spatial filtering in parallel may provide an account of the initial global stage of processing and axis selection in the two stage models proposed by Bruce and Morgan (1975) and Palmer and Hemenway (1978).

The observed effects of pattern form (element type and spatial grouping) are also compatible with a filtering model. Coarse scale spatial filters will respond more strongly to the sudden changes in mean contrast produced by dense local clusters of elements than to the smaller changes which occur across a uniform distribution of elements. Dakin and Watt (1995) propose that the response characteristics of anisotropic filters may also explain the axis effect observed by Bruce and Morgan (1975); Barlow and Reeves (1979); Jenkins (1982) and Wagemans et al. (1990), and the detrimental effect of mixing the contrast within pairs observed by Zhang (1992). Elements, or clusters of elements close to the axis elicit single elongated filter responses which traverse, and are aligned about the axis. These elongated responses are only obtained under conditions where the matched elements are of the same contrast, therefore the symmetric positional relations in patterns of mixed contrast dot pairs would not emerge as single responses at coarse spatial scales.

The implication of a filter based model of symmetry detection is that the emergence of global symmetric structure may be explained in part by the operation of general purpose visual mechanisms. If this is the case then the perception of bilateral symmetry cannot be divorced from the perception of other types of structure which share certain types of regularity in common with symmetry. Thus, in order to generate some general principles about the detection of regular structure in images it is necessary to determine those aspects of bilateral symmetry which make it a particularly salient structure, but which are not necessarily unique to symmetry. It is also necessary to identify those patterns which share these salient features in common with bilateral symmetry.

Such patterns will not necessarily be other symmetry types. Royer (1981) proposes a model of structure detection based on the observation that different classes of symmetry (such as horizontal, vertical, diagonal, centric, rotational, and multiple axis symmetry) have spatial transformations and therefore visual features in common. These are extracted, he claims, in a hierarchical fashion by orientation channels operating in parallel. In order to arrive at the correct representation of the stimulus a hierarchical elimination of higher order candidate structures is required. However, the highest level of structure description in this model must be extremely general to contain a description of all possible symmetry transformations. Whilst perfectly regular symmetries are easily classified and easily discriminated from other symmetry types, it is difficult to imagine the basis on which such a model could reject an unstructured stimulus, or discriminate irregular symmetry from noise, given the generality of the initial structure description.

In order to establish the general mechanism used in symmetry detection there is a need to identify a set of salient visual features which are sufficiently low-level that the transformation used to produce the pattern is not relevant. These features should be both common to many structures, yet sufficiently well circumscribed they do not describe every structure.

1.5.2 Component processes in symmetry detection

Jenkins (1983b), proposes a model for symmetry detection which is based on the extraction of low-level structure. Jenkins uses a definition of symmetry which, in a departure from the traditional definition, describes the visual features of the pattern rather than the reflected relationship between the elements. He describes a symmetric dot pattern as, "...a two dimensional distribution of uniformly oriented point pair elements, of nonuniform size and with collinear midpoints" (p. 433). Jenkins identifies three component processes in symmetry detection, the first of which is the detection of orientational uniformity between point pairs, followed by the fusing of the most salient (locally paired) points into a single central feature, then a final assessment stage which determines whether the feature is symmetric. The first two of these processes are not specialised for symmetry and could feasibly be carried out by oriented spatial filters which will produce strong 'fused' responses to pairs closely matched in the same orientation as the filter (and will emerge from the operation of oriented filters). The third component process is symmetry specific, but this occurs only after the low-level structure has been extracted, and may be carried out to varying degrees of precision depending on the specificity of the information demanded by the task (e.g., depending whether symmetric structure is simply to be detected or discriminated from another regular structure). Jenkins points out that a process which detects orientation information in a single location is more compatible with known neurophysiology than a process which involves pointwise comparison of reflected elements.

An alternative way to understand Jenkins model is in terms of the visual features that are detected by the three component processes. The first two processes which detect orientational uniformity and then fuse the central features are in effect extracting elongated features which are positioned in parallel. Thus, the visual features of elongation and parallelism are sufficient for the perception of structure (Jenkins, 1983b, Experiment 1) whilst the detection of bilateral symmetry (as opposed to another regular structure) requires the third process which detects whether these elongated and parallel structures are aligned about a single midpoint.

Jenkins description of symmetry is interesting, not only because it describes the visual aspects of symmetry but also because it breaks down the unitary description of reflection into lower level components which are non-unique. If the reflected relationship is not explicitly perceived in symmetry detection then it is unlikely that symmetry is uniquely represented, making a specialised symmetry detection mechanism unnecessary.

Jenkins applies this model to the detection of point pairs; however, it is feasible that the same processes be applied to detect parallelism and alignment between larger scale clusters of points. Jenkins stimuli comprised dynamic symmetric textures which may have different statistical properties from static random dot patterns, therefore the application of this model to large scale or grouped features requires further investigation.

1.5.3 The saliency of symmetry re-examined

Baylis and Driver (1994) observe that the detection advantage for symmetry over repetition seems paradoxical, given that repetition only involves the repositioning of image features, whilst symmetry involves both a repositioning and a reflection. As noted, the visual qualities of the pattern cannot necessarily be inferred from a description of the transformation used to generate the pattern. The perceptual difference between symmetry and repetition may be understood by considering the low-level content of the patterns rather than the transformation.

For example, the fact that symmetry is more salient than other pattern structures such as repetition (e.g., Bruce and Morgan, 1975; Corballis and Roldan, 1974; Baylis and Driver, 1994) need not implicate a dedicated symmetry detection mechanism, or a special status for reflected structure. Instead, the particular detectability of symmetry may have a much more general explanation. This can be seen by examining the visual properties of symmetric (and similar) patterns.

The importance of information near the axis is well documented for different sorts of tasks and different kinds of stimuli (Bruce and Morgan, 1975; Barlow and Reeves, 1979; Jenkins, 1982; Labonte et al., 1995). Beyond the axis region the pattern saliency falls considerably and then rises again in the region of the pattern outline. Because in each of these studies the axis was presented at fixation, it is not clear whether the information close to the axis is salient simply because it is closest to the fixation point, or whether the axis is particularly salient because of the nature of the information present in that region. Whichever of these is true, the greater detectability of symmetry over repetition may be due to the fact that symmetric patterns are more likely to contain information in the axis region. The reason for this is that in symmetric patterns, the elements are paired at a range of distances, therefore at least some of the pairs will fall close together around the axis. In repeated patterns elements are paired at a constant separation and therefore (depending on the distance used in the task), the very close matches that occur in symmetric structure will not be present. Thus, it is possible that both the axis effect and the greater saliency of symmetric structure are a function of point pair separation and the number of point pairs falling close to the axis. Julesz (1975) and Tyler and Chang (1977) found that detectability of repeated structure is a function of point pair separation; however, the separation between points is rarely a consideration in comparisons between symmetric and repeated structure and is typically set to one half of the pattern width.

An additional reason for the saliency of symmetry over repetition may be that features with midpoint collinearity have particular visual significance. Matched pairs are perfectly collinear in symmetric patterns, whereas in repeated patterns collinearity is disrupted, although often restricted to a certain range. The detection of parallel structure is found to improve as the midpoint collinearity of point pairs is increased (Jenkins 1983b). This may be because a single axis through a group of point pairs provides a well specified anchor point for investigating the stimulus (Tyler and Chang, 1977). Another possible explanation is that a single axis defines the centroid of a pattern in one direction and this may have some function in locating and representing structure.

Thus, the particular saliency of symmetric structure may be due to the number, proximity, perfect parallelism, and collinearity of point pairs, or some combination of these things. Where these factors are disrupted or distorted, as in repeated structure or natural (approximate) symmetries the detectability of the pattern would be expected to decrease. A special mechanism may not be necessary to account for the detection advantage for symmetry as this advantage can be equally explained in terms of different levels of optimality amongst different pattern types for the same mechanism.

1.5.4 Correlation quadrangles

Wagemans (1991; 1995) rules out Jenkins' model of symmetry detection on the grounds that the detection of orientational uniformity and midpoint collinearity is insufficient for the detection of global symmetry. The evidence for this comes from experiments which find that skew symmetry is much harder to detect preattentively than bilateral symmetry, despite the fact that first order relations, defined by orientational uniformity and midpoint collinearity, are present in both pattern types. Given this, Wagemans (1991) proposes that higher order relations between element pairs must also be involved in the representation of global symmetry. These higher order relations emerge from the quadrilateral structures which are present between pairs of dots. In bilaterally symmetric structure the angles of these quadrilaterals are equal and opposite and therefore perfectly regular. Initial detection of this regularity initiates a reference frame which specifies both the axis orientation and the orientation of the virtual lines. Further pairwise matches are propagated within the constraints of that frame, at the same time reducing the number of possible incorrect matches. This process builds in momentum, and is termed 'bootstrapping' by Wagemans et al. (1991).

Wagemans et al. propose that skew symmetry is difficult to detect because the second order statistics are irregular and therefore introduce some uncertainty into the bootstrapping process which is slowed or stopped as a result.

However, skewing causes some other changes to pattern structure which may account, at least in part for the effect of this transform on detection performance. It has the effect of distorting the local clusters of elements either side of the axis, such that although the first order regularities between elements are preserved under the skewing transformation, the symmetric relationships between the cluster pairs are disrupted. First order regularities are therefore preserved only at the level of individual dots, whilst global features fractionate and disappear (Wagemans et al., 1990; 1992). Thus, it is possible that the effects of skewing are not only due to the irregularities in the second order relations, but partly due to the fact that skewing disrupts grouping processes with the result that the first order statistics are effectively absent at a scale appropriate for global detection (Wagemans et al., 1992).

It would therefore be of interest to discover whether skewing disrupts performance more severely in uniformly distributed patterns than in dense or 'clustered' patterns, and also if patterns comprised of large coherent features which will do not fractionate are more easily detected than both of these. For example, Wagemans (1992; 1993; 1995) observed that skewing is less disruptive in polygon patterns, where points on the pattern are explicitly connected than in dot patterns where the connections are 'virtual' connections.

Aware of the possible interaction between skew and grouping, Wagemans et al. (1990; 1991) are careful in their experiments to disconfound global and local strategies, focusing both the model and their experiments on the fine scale detection of individual point pairs. Notably, they deliberately use uniformly distributed dots for the purpose of eliminating clusters, thereby reducing the opportunity for subjects to use a global detection strategy.

As a consequence of this, the bootstrapping model is highly specific to a certain type of symmetry. It operates at the level of dot pairs and does not for example account for symmetry detection at unknown orientation or position in the visual field (Wagemans, 1995).

Attempts to extend the operation of the bootstrapping model to encompass these conditions at the level of individual dots are likely to meet with a combinatorial problem. Given a pattern comprised of identical elements, and no basis for the initial selection of pairs to test, the number of possible matches is enormous and other experimental conditions such as noise and smearing of the stimulus will increase it further. At the pairwise level, there is no obvious way to select the initial pairs for testing, however the combinatorial problem may be reduced by grouping local clusters of dots prior to matching in order that the position of groups rather than individual elements can be compared. There may be other solutions to the problem, however, if grouping is invoked to generalise the model to deal with orientational and positional uncertainty, it may be found to have the same facilitating effect on the detection of skew symmetry. The effects of grouping on both human performance and the bootstrapping model in the detection of skew symmetry will therefore have to be considered. If the effect of grouping is to reduce the number of groups to be matched therefore the bootstrapping process will be shortened, as it is only required to compute parallel relations between a few groups rather than many pairs. Thus, the bootstrapping under conditions of global structure may be rather similar to Jenkins detection of orientational uniformity. It is possible that the bootstrapping model as it currently stands, and Jenkins three components model are specialised for different tasks, or for detection under different stimulus conditions.

1.6 Conclusion

The general conclusion of this chapter is that symmetry does not describe a single class of pattern, but includes a variety of patterns which are perceptually different, and which may be detected by different mechanisms. In light of this, the approach to symmetry perception suggested here is to focus on one type of symmetry detection task, and as the interest here is in those patterns which can be detected presegmentally, to determine the visually significant features of symmetry which enable presegmental detection.

However, the difficulty in investigating presegmental symmetry detection is that there are no fixed assumptions, that is, there is neither a mechanism or a definite pattern description around which to base an investigation. The suggested solution is to consider symmetry perception in the wider context of pattern processing. Few studies have specifically investigated the role of early visual processing in symmetry perception, however, the human visual system is capable of detecting many classes of pattern (e.g., collinearity, common orientation, elongation, rotational, and repetitive structure), without explicit or high-level knowledge of the pattern structure or content. If common attributes of patterns (including symmetry) that are grouped in this way can be identified, common detection mechanisms may also be revealed.

Thus is proposed that a useful approach to the study of presegmental symmetry detection is to consider symmetry as one of a class of patterns which have in common, general properties that are readily detected by the visual system and to identify these common properties and the conditions under which they are detectable. This idea is expanded in Chapter 2.

2

IMAGE SEGMENTATION

The purpose of vision is to allow us to see what to do and how to do it. In order to perform purposeful actions and plan appropriate responses to the structures and events in our environment, it is necessary to segment the environment into manageable parts in such a way that is useful for acting upon those parts. We must segment the visual scene into objects.

Segmentation is not simply an abstract or theoretical stage of visual processing, but is essential to all purposeful action. Blind humans and animals must also correctly segment their physical environment using other senses in order to navigate and act upon the world. A sense of vision confers the advantage of planning action in advance, even in novel or unfamiliar situations.

Typically, actions are not performed upon a whole scene, but rather on localised parts of the scene, which will be described as 'objects'. There is no single comprehensive description of an 'object' as the definition of 'objectness' is heavily dependent on both task and context. For example, a single leaf may be described as an object; it can be picked up, dropped, or otherwise manipulated in various ways. Similarly, a tree may be described as an object; it can be leaned on, hidden behind, chopped down, etc.. At a distance where both the leaf and tree can be resolved, it is the selected action that determines which is the object.

Despite the lack of a precise definition, objects have certain observable characteristics which may be useful for segmentation. In order to prompt a purposeful action objects must be in some way meaningful to the observer and visually distinct from their surround. They tend to be localised, independent and circumscribed in space: they are coherent and compact. If we assume that the image features which correspond to objects also have these characteristics, in theory we can use these to segment the image into smaller parts which correspond to objects.

The raw material for the visual process is a 2 dimensional array of pointwise light intensities projected on to the retina. Visual segmentation of a scene into its constituent objects requires that the 2 dimensional image of the scene be broken down into image structures which correspond to objects.

In practise this is not a straightforward task. The raw image is a complex pattern of intensity changes which are only in part attributable to significant structural changes in the scene. Each point in the image is determined by a combination of factors such as the nature of the light source, the reflectance of surface materials, the angle of reflectance and the distance and relative position of the observer to the light source and the surface. The complexity of the relationship between the various factors and the final image structure is such that there is no single relationship between the significant structural content of a scene and the corresponding image value, therefore a direct translation from image pixel values to interpreted physical structure is impracticable.

The segmentation of raw images into structures which correspond to objects must therefore be achieved via a more indirect route.

Approaches to image segmentation can be broadly divided into the two categories of those which attempt to explicitly draw scene content and geometry from images (scene content approach), and those which describe the image content as a precursor to making inferences about the properties or contents of the scene (image content approach).

2.1 Scene content approach to segmentation

The basis of the scene content approach to segmentation is to segment the image into primitives which correspond directly to objects or parts of objects. Within this approach, a variety of techniques have been used which themselves differ in the complexity of the description that is sought in the initial segmentation.

2.1.1 Direct segmentation into objects

The direct segmentation of images into labelled objects is no longer proposed as a realistic approach to image segmentation, but is characterised here to illustrate the nature of the segmentation problem. The traditional approach to pattern processing was preoccupied with devising algorithms to carry out discrete symbol recognition. Since objects, or segments of the scene are the goal, a natural starting point is to consider whether each object can be directly segmented from the image of the scene. In practice, this amounts to assessing the image to establish whether it contains each of a set of known, pre-identified objects (Kasvand, 1972).

The 'segment and label' approach of early computer vision research proposed that images could be segmented directly into objects by matching the current image to stored templates. In the extreme case, this method requires that the stored templates consist of complete scene descriptions which are directly matched to the image. However, the boundless complexity and novelty of natural images makes the use of such a high-level primitive unfeasible, as a separate template would be required for every possible scene, including novel scenes. Matching at the level of whole images or scenes would therefore be encumbered with the difficulties of storage, selection, and retrieval in an infinite set of image templates.

For example, how might templates be categorised for storage and maximum efficiency in matching (e.g., by semantic category or visual similarity)? How might novel scenes be dealt with given no stored template for matching? By what mechanism might a particular template be finally selected? Selection by trial and error would be a lengthy, iterative process and would require some high-level criterion for accepting a successful match.

One possible method for reducing the number of stored templates is to match to stored representations at the level of scene components (i.e., objects) rather than whole scenes. In theory, this would mean that an object could be matched to a template independently of surrounding scene content and therefore that one template per object would be required rather than one template for each instance of that object.

However, direct segmentation at the slightly lower level of object templates is also unfeasible, as the matching of object templates requires that the scene has already been decomposed into object descriptions. It therefore fails to address the initial segmentation problem of breaking the raw image down into its component parts. In addition, this method is frustrated by the combinatorial explosion of possible exemplars of even a single object under different viewpoints, viewing distances and lighting conditions.

The difficulties encountered by the template matching approach indicate that images cannot be reliably segmented into complete object structures. A more general expression of this problem is that there is a trade off between the complexity of a primitive representation and the reliability with which the primitive can be detected.

An alternative to this is to construct a low-level representation of the image comprised of very simple primitives which are reliably detected and which are common to most objects and scenes. This low-level representation need not find complete, nameable objects but simply primitive structural features in the image which may indicate the presence, nature and location of an object in the scene. By describing the scene contents so, the number of templates required for matching should be vastly reduced, as many objects will share structural primitives. Moreover, scene descriptions at the level of structural contents should allow the processing of novel scenes, as structural analogies will be found to exist between familiar and novel situations (Narasimhan, 1970).

2.1.2 Segmentation into primitive object structures

If whole objects are computationally difficult to recover from images directly, it may be the case that parts of objects are more easily and reliably detected. Were this the case, then high-level object descriptions could be constructed after detecting more primitive object features, such as surfaces and edges. The issue then becomes whether there are primitive features that can be reliably identified from image luminance patterns.

Surfaces

The extraction of low-level primitives which correspond to object features would require general constraints on the natural world. One potential constraint on the nature of physical structure might be that objects are made up of surfaces which are typically smooth, uniform and extensive. Such surfaces will reflect light uniformly, therefore where this constraint holds, object surfaces will be manifest in images as extensive regions of uniform luminance.

In practice, the constraints on the nature of object surfaces are not sufficiently strong to allow local scene structure to be extracted directly from images. Surfaces, and their corresponding image functions are unconstrained in a number of ways.

Many objects, particularly natural objects are not composed of flat, uniform surfaces. Marr (1982) points out that certain types of surface (e.g., wheat fields and cats coats) have complex and elaborate reflectance functions and can only be regarded as having the defining surface properties within a hierarchical organisation of spatial structure. Thus, the uniformity assumption is based on the observation that items at one level or scale of processing in this hierarchy are more self similar than items at different levels. This means that surface primitives cannot be extracted directly on the basis of uniform luminance, but instead must depend on a pre-processing stage which assesses local similarity. Typically, some sort of local averaging is used to achieve a representative surface, however such solutions introduce uncertainty into the segmentation. The main sources of uncertainty are about the appropriateness of the area over which averaging takes place, the representativeness of the average value, and the accuracy with which the surface boundaries are positioned (Wilson and Spann, 1988). These problems reveal the rather circular logic that is used in defining surfaces. Surfaces are defined by the properties of smoothness and uniformity in an image region, however, image regions are more likely to be ascribed uniformity if they are believed to belong to the same surface.

However, even if the uniformity constraint is accepted, there are further problems associated with the extraction of surface primitives. The image of a surface has a pattern of luminance that depends not only on the reflectance properties of the surface, but also on the illumination of the surface, the shape of the surface, and the viewing direction. The consequence of these factors is that images of surfaces are highly variable. Two surfaces of the same shape, or the same surface under different illuminants can give rise to very different patterns of luminance in the image.

There is a wide range of surface materials in the world which have a variety of reflectance properties. As a consequence, the reflectances and the corresponding image luminances will be widely variable between surfaces. If a surface is specular there will be illumination highlights reflected which disrupt the uniformity. Surfaces have variable shapes. This is a problem for segmentation of images into surfaces because surface contours will give rise to shadows, creases in the surface will be marked by different luminances, and even flat, smooth surfaces will typically have luminance gradients caused by the orientation changes in the surface.

Thus, surfaces will typically project highly specific patterns of luminance that are determined by both surface reflectance and surface geometry. The reason why this poses a serious difficulty for attempts to segment images into surfaces is that in practice, surfaces are not constrained by the simple properties of smoothness and uniformity and cannot therefore be considered to be universal, low-level primitives. Given the wide variation between surfaces, almost as wide a range of surface templates would be required for surface selection as would be required for high-level object detection.

Edges

A slightly different approach to the detection of object structure is to extract not object surfaces, but occluding contours and significant features on surfaces of objects. Objects are easily recognised from line drawings which depict only outlines and simplified features, therefore it might be assumed that an adequate representation of shape can be constructed from low-level features such as edges, creases and corners. The physical constraint assumed in the edge based approach to segmentation is that occluding contours and feature contours are rigid and continuous. In three dimensional visual scenes, occluding contours are marked by a sudden discontinuity of a surface material, whilst creases and corners are marked by a change in the orientation of the surface material with respect to the viewer. In a two dimensional projection of the scene, the effect of both cases will be a corresponding change in the image luminance. These changes in luminance are referred to as edges. Edges can be described as image features which are characterised by rapid luminance change in one direction and luminance continuity in the orthogonal direction.

In practice, there are a number of difficulties in identifying occluding contours from luminance patterns in images. Surface features, and their corresponding image functions are unconstrained in a number of ways.

Whilst a sudden luminance change might be expected in response to an occluding contour, the amplitude of the change is dependent on the luminance contrast between adjacent surfaces and is therefore highly variable. Occluding contours may be marked by sudden but very low luminance changes, whilst much larger changes may arise due to effects of lighting and shadowing. There is insufficient information in the image to determine the cause of any image edge.

Significant structural features do not necessarily give rise to sudden changes in image luminance, but cause changes at a range of gradients, according to the structure in the scene. Surface creases are likely to give rise to relatively gradual luminance gradients in comparison with occluding contours. Given that both significant changes and changes due to other causes will be manifest in the image at a range of luminance gradients it is not possible to identify the significant structural changes on the basis of the image data alone.

Physical contours can be said to be rigid in that a break in the contour continuity implies a break in the surface, a sharp change in orientation or some such structural feature. The third requirement for the detection of edge and feature correlates in images must therefore be that continuous contours in the scene should give rise to corresponding, unbroken lengths of constant luminance change in the image. Under this constraint, breaks in the continuity of the image feature could be interpreted as significant structural changes. However, this relationship does not hold for the reason that luminance is not necessarily constant even along a smooth physical edge, but is dependent on the reflectance of the surface edge and the effects of lighting which may vary locally, particularly in specular surfaces. The effects of illumination may also vary with viewing angle, the consequence of this being that the luminance edge will shift relative to the physical edge. Where the continuity of an edge is broken, there is insufficient information in the image to determine whether this is due to a physical discontinuity or to non-structural effects such as shadowing and specularity.

Thus, object occluding contours will typically project highly specific patterns of luminance that are determined by the nature of the object and its neighbours, the local and global effects of illumination and the direction from which it is viewed. Edges in images are not constrained by the simple properties of rapid change in the direction orthogonal to the edge and constant luminance in the direction of the edge and therefore cannot be captured by simple, reliable primitives. Image structures due to physical edges are not sufficiently constrained that they are differentiable from image structures due to other causes.

Geons

Another proposal for the extraction of scene features from images is that of "recognition by components" (Biederman, 1987). The central tenet of this approach is that certain properties of objects (e.g., curvillinearity, collinearity and cotermination) will be preserved in the visual image. These properties are termed *non-accidental* properties, and it is proposed that object structures can be inferred where these are found in the image.

Biederman proposes that all objects are composed of members of a finite set of geometric primitives (geons). Images are parsed at points of convexity, concavity and cotermination to obtain these geons, which are then organised and grouped around the central principle of non-accidental properties. The resulting arrangement of components can then be matched to an existing template. Because the geons are simple, and finite in number, matching is thought to be robust to stimulus degradation and other sources of uncertainty (e.g., caused by partial occlusion).

For the purposes of extracting scene features from images, this approach appears promising. It is based on the detection of features which are not object specific, yet are common to all objects and proposes simple principles for determining the relationships between features. However, it is not adequate as a method of segmentation, for the reason that it is essentially an edge based approach. It cannot be applied to raw images, but depends on a preceding stage of edge extraction which is required to produce, not only an edge map of the image, but more specifically an edge map of the object — in effect a line drawing which makes explicit the boundary and the internal structural features of the object. The extraction of structural components is therefore not only subject to the practical problems of edge detection (i.e., locating significant continuous edges), but requires that structural features (such as boundaries) be specified. The selection of boundary edges and feature junctions is possible in vastly simplified representations of objects with no confounding effects of illumination or shadowing and no surrounding features and the exemplar objects used by Biederman are of this kind. However in natural images, these features cannot be extracted at a low-level, and even with high-level guidance there is considerable disagreement amongst researchers as to what constitutes a boundary or feature edge (Mowforth and Gillespie, 1987).

Biederman recognises this limitation of the theory, and does not suggest that it be used for low-level segmentation. However, the limitations of the approach provide a clear illustration of the problems inherent in extracting scene features directly from images, whether these features are surfaces, edges or structural primitives.

2.1.3 Summary of scene content approach

The general problem with the direct extraction of scene features and geometry from images is that the physical world is not tightly constrained by assumptions such as uniformity, continuity and rigidity. These assumptions are idealised and overgeneralised and therefore weak in practice. The weakness of the constraints is compounded by the fact that images of scenes are not only determined by physical structure, but by interactions between structure, lighting, and viewpoint. The relationships between these factors are underdetermined in natural images and there is no way to infer the physical cause of an image primitive directly from the image data. The direct extraction of physical features and scene geometry would require that structural features give rise to image structures which are simple, reliable, highly constrained and unique. However, a segmentation mechanism which relies on unique features cannot be said to be low-level, as the feature detection would require direct matching to be carried out between the current image feature and some stored feature template.

There is a further, more fundamental problem with the approach which seeks to segment images by finding structural features. Edges, geons, and surfaces are not generic features, and this means that even when the structural features in an image are clearly delineated, there is no a priori way to determine which of these are essential for segmentation. The level of structural detail required in a scene or object representation will be heavily task dependent. In this sense, feature detectors are little more constrained than high-level object detectors, as logically it is necessary to know what information the features contain before the image is segmented.

2.2 Image content approach

The image content approach to segmentation is to initially consider only the pattern that is present in the image, and to segment the image into primitives or regions which show an apparent coherence or uniformity in image pattern. Only after this can consideration be given to the nature of the objects to which these image segments might correspond. The theory is that image patterns, where they exist, can be found easily, and that seeking appropriate patterns will lead to approximately appropriate segmentation much of the time.

The image content approach differs from the scene content method in that where a template matching or feature based method seeks approximate image matches to precisely defined physical structures, this approach seeks the reliable detection of precisely defined image structures which only correspond loosely to physical structure. The segments so identified in an image can then be treated as 'objects' and may be useful for some tasks even in their early, ill defined state.

2.2.1 Segmenting by discontinuities

A number of approaches have been employed to identify the general underlying principles of low-level segmentation and the pattern properties which are amenable to this. Common to these principles is the idea that that local image regions, which are characterised by least change in one or more variables, should be treated as coherent image segments. The corollary of the least change principle is that of maximum change, where local image regions that are delineated by discontinuities should be treated as independent image segments.

Using this approach, the segmentation issue becomes one of identifying those image properties which yield the most useful segments. Images are two dimensional luminance functions, therefore an obvious segmentation is into regions of uniform luminance, which by nature will be bounded by luminance discontinuities. This is not a straightforward task, as natural images are continuously changing luminance functions and changes occur over a wide range of scales. Segmentation of the image into uniform regions therefore requires that only the significant changes are treated as discontinuities; however, what constitutes significant change is also variable, both between images and locally within an image. For this reason there can be no single, predefined criterion for finding significant discontinuities in raw images.

2.2.2 Zero crossings

Given that 'uniformity' and 'discontinuity' cannot be defined absolutely in raw images, one proposed method of segmentation is to constrain the image content by restricting the range of scales over which change takes place. A single measure of luminance change can then be used, which is defined in relation to local image content. Marr and Hildreth (1980) proposed that discontinuities could be detected at a range of scales by smoothing the image locally and finding zero crossings in the second derivative of the luminance function. In this way, a new representation of the image is obtained, in which the 'significant' points in the image are taken to be those where the rate of luminance change is fastest. Significance is therefore determined purely within the image domain.

The next task is then to recombine the representations at different scales and this is enabled by the fact that intensity changes do not occur arbitrarily in images. The physical features which give rise to intensity changes tend to be spatially localised in the image, thus, the location of scene features can be inferred from the spatial coincidence of zero crossings across a range of scales. It is important to note that this method does not imply any specific knowledge of scene content, or even of primitive scene features such as edges. It simply provides a means for the most appropriate segmentation of the image.

It is possible to extend the concept of uniformity and discontinuity to pattern dimensions other than luminance. For example, images are readily segmented into regions that are delineated by discontinuities in colour, curvature, tilt, colour, line ends, elongation, and movement (Treisman, 1986). Discontinuities in any of these properties can be reliably measured, and the images accurately and reliably segmented into the chosen primitives using only the information that is present in the image and without recourse to predetermined templates for physical structure.

The image content approach is therefore successful insofar as it can be used to extract low-level image structures which are simple, well defined, locally defined and general to a broad range of images. However, the detection of local continuity in images does not imply a computational procedure for scene segmentation. Natural images have complex reflectance functions and structural features are not necessarily delineated by regions of local continuity. Effects of lighting and viewpoint may serve to introduce spurious discontinuities in images and also to mask or disrupt these where they exist. The purpose of segmentation is not simply to break down images into regions of statistical uniformity, but to find objects, and the trade off for the highly accurate and reliable detection of low-level image primitives is that the primitives extracted carry no inherent visual significance. Image content analysis simply produces a description of the image which will contain false targets (i.e., non-structural changes) as well as object features and there is no basis, given only the image data, for discriminating the information content of the primitives extracted.

In other words, low-level image primitives are of little direct use as there is no way of knowing which of them, if any, correspond to physical scene structure. Some further interpretation is required in order to obtain a segmentation which is meaningful as well as reliable.

2.3 Combining high and low-level approaches in image segmentation

The information required for scene segmentation cannot be directly extracted from images using high-level, 'object centred' techniques because objects and object parts are underconstrained, nor can it be directly inferred from image descriptions or image statistics, because these have no direct correspondence to scene structure. Evidently, an intermediate level of processing is needed to organise and group low-level visual primitives into object structures. Such a process implies the use of high-level guidance in the interpretation of low-level descriptions. An intermediate level of object description is required which is not dependent upon specific knowledge of scene content, but which can be used to group low-level primitives in a way that corresponds to the presence of objects or meaningful structure. In other words a general model of object structure is required which will provide some method for identifying the most visually significant image structures.

A possible solution to the segmentation problem is to identify generalised properties of objects which could be captured by simple grouping heuristics. If appropriate, these heuristics would provide grouping principles which describe relatively stable or predictable relationships between low-level primitives. Such principles would of necessity be determined by similarly stable or predictable structures in the physical world.

The use of generalised grouping heuristics in image segmentation is enabled by the fact that objects tend to be spatially circumscribed and cohesive over space and time. Objects tend to come about through some unified cause or process such growth and accretion or erosion and many objects, natural and manufactured, are limited in form by the need for stability under gravity. Coherent objects are therefore likely to contain structural regularities which will be manifest in regularities or homogeneity in the image domain. Regularities in images are unlikely to arise by accident (Stevens, 1981; Marr, 1982; Witkin and Tenenbaum, 1983; Kass and Witkin, 1987) therefore regions of spatial cohesion and regular structure in an image are good indicators of a single underlying physical cause, and therefore indicate the presence of an image region which may be significant for behaviour.

The identification of stable structural relationships in images is very much an intermediate visual process. Collins dictionary defines structure as "*the arrangement and interrelationship of parts in a construction*" (p.1512). Structure describes orderly, regular or coherent patterns and relationships. Where these relationships are known they can be applied to image descriptions to group subsets of primitives which belong together. Structure cannot be directly extracted from grey level images, for the same reasons that objects, surfaces and edges cannot be detected — each possible structure would have to be either very highly constrained or represented in one of a store of possible templates matched to the raw image.

The extraction of structure is therefore dependent upon the preceding primitive representation which breaks the image down into consistent or uniform regions. Only then can structural descriptions be used to find relationships between these well defined image primitives. The advantage of looking for structural relationships rather than primitives is that independent primitive image segments that are defined by uniformity and continuity can now be merged into more complex perceptual units which extend beyond the limitations of statistical descriptions. Thus, the detection of stable structure is not a low-level process. It is not used to extract image primitives, but rather operates on primitive representations. Nor is it a high-level, template matching process, as it is not used to extract nameable objects or object specific features.

Structure describes the stable physical relationships between object parts. Unlike surface reflectances, these relationships are not changed as a consequence of unusual lighting or viewing position. Thus, where stable relationships between primitives can be formed these will be unaffected by gross changes in lighting and viewpoint, and furthermore will provide some external means of interpreting image content under unusual lighting or viewing conditions. Although structural descriptions are much lower level representations than specific feature or object templates, the relationships that are sought at this level of representation must somehow be specified. It is once again necessary to avoid any sort of template matching in the extraction of image structure. For example, one strategy might be to construct a set of measurable stable structures for matching to image descriptions. However, strict regularity rarely arises in natural images and such a technique would immediately fall into the template matching trap of having to somehow evaluate approximate matches to strictly defined, overconstrained structures, and would also raise the problem of combining templates for matching to complex structures. Variability is an intrinsic and important characteristic of natural images therefore it is essential to accommodate it by using processes which are relatively flexible rather than attempt to manage it with rigid constraints which often prove to be weak and error prone.

The grouping of primitives in natural images therefore requires some specification of structure which is responsive to highly regular structure but which is also tolerant to deviation from precisely defined relationships. The method proposed here is to use generalised grouping heuristics which exploit high order regularity in the image. The reason for this is that the overall strength of any structure will be determined by both the regularity of the structure and the number of regularities it contains. In other words, the more complex. a structure is, the more confident we can be that it has not arisen by accident. Variability in image structure on one dimension may therefore be compensated by the presence of structure on another dimension. For example, a straight line of identical dots is a highly regular and visually significant structure, defined only by linearity. The visual significance of the single line structure will be reduced if the linearity is disrupted; however, two such rows of dots in parallel contain a higher order structure which remains regular despite irregularity in the component parts. The visual significance of approximate structure in one dimension is therefore determined not only by any absolute measure of regularity on that dimension, but also by the confirmatory presence of structure on a number of other dimensions.

2.3.1 The Gestalt approach to structure perception

The requirements of generalised structure as defined so far are that it must be independent of specific scene content, yet characteristic of general object structure. It is possible that the Gestalt principles of organisation fulfil both requirements of intermediate level vision. Some of the factors that determine visual grouping were described by the Gestalt psychologists as the 'principles of perceptual organisation'. The Gestalt principles describe a set of spatial relationships between elements which produce coherent, stable patterns, even in the absence of high-level knowledge to guide the interpretation. The grouping principles are therefore independent of specific scene knowledge. However, the Gestalt principles were relatively abstract and described in terms of pattern attributes rather than in terms of how they might function in a coherent perceptual framework. Thus, where the pattern attributes specified in the Gestalt principles can be shown to be approximately related to object structure, these may provide the intermediate step between low-level visual primitives and higher level object structure.

Objects have a number of observable properties which may appear singly or in different combinations. The list given below is by no means exhaustive.

Consistency:	Objects are comprised of matter which tends to be stable and coherent over space and time. Objects, or parts of objects comprised of the same matter are likely to show uniformity or consistency (Marr, 1982; Watt, 1988).
Elongation:	Objects tend to have an axis of elongation which is often an axis of symmetry (Marr, 1982).
Boundedness:	Objects are necessarily bounded and spatially localised (Julesz, 1971).
Regularity:	Objects tend to possess a number of invariant or non-accidental properties which are reflected as regularities, such as parallelism, alignment, and symmetry, in the visual image (Biederman, 1987).

The object characteristics as described above can be categorised into two types — those which describe the characteristics of primitives which facilitate grouping of elements (i.e., consistency), and those which describe higher level relations between primitives which facilitate the separation of the object from the background (binding principles). The Gestalt principles of organisation can also be divided into these two categories. The first of these is very similar to the basic premise of texture segregation, that primitives which are uniform or consistent on some dimension will tend to be grouped. In Gestalt terms these are known as the principles of grouping by similarity and proximity. The similarity principle states that elements which look similar tend to be grouped together. The Gestalt principle of grouping by similarity is approximately the perceptual equivalent of texture segregation by local size, colour, brightness, contrast or orientation. The proximity principle states that elements that are close together tend to be grouped. This Gestalt principle could alternatively be expressed in terms of low-level texture segregation and the extraction of local density boundaries. Both principles state that regions which are locally uniform on some dimension will give rise to bounded regions marked by discontinuities or boundaries on that dimension. These principles may therefore capture the uniformity within and nonuniformity between objects and regions. To the degree that uniformity characterises a particular object, similarity and density may be used as a segmentation cue. However, uniformity tends to characterise primitives (or surfaces of objects) rather than whole objects and where this is true, some higher level of organisation is required to bind primitives into object structures.

The Gestalt principles that are primarily concerned with the grouping or binding of pattern elements and primitives into preferred structures are those of good continuation, closure, relative size and symmetry. The binding principles are expressed by the law of Praegnanz which states that, of a number of geometrically possible organisations, elements will be bounded into the one that offers the simplest and most stable interpretation (Koffka, 1935). In abstract, the principle of Praegnanz is too vague to have any predictive power because terms such as 'simplest' and 'best' are not well specified and carry no inherent meaning. It is argued here that the 'goodness' of form may be determined, not by intrinsic characteristics of the form, but by the frequency with which that particular form is observed in the external world. It is therefore possible that the frequently observed, general characteristics of objects are captured in the Gestalt principles and expressed as abstract grouping rules. If object structure is the basis of the Gestalt principles, then they can no longer be considered to be abstract, vague and overgeneral, but are highly predictive and thoroughly tested by the successes and failures of visually guided actions based on the groupings performed and interpretations made on the basis of these groupings.

For the Gestalt principles of organisation to be used in segmentation, it is necessary that these are not only representative of object structure, but also that they are manifest in images as global image structure which is easily detected. The function of early image segmentation is to signal the presence, location, size and perhaps nature of parts of the visual image which may warrant further attention, and the result of this stage of vision need not be recognisable objects, but simply generalised object descriptions. In order to be of practical use, the range of structures detected by such a system must be restricted in order to limit the number of false alarms given at this early stage. A large number of detectable structures would increase the number of possible structures in any image and require some basis for selection between these.

It is argued here that the range and the complexity of image structures required for a generalised object description is greatly reduced by virtue of the fact that the Gestalt type structures described above can be fully described in the image domain by a limited set of simple features. The principles of similarity and proximity are manifest as regions of uniformity along some dimension (contrast, orientation, density, etc.), which are detected at a low-level and which indicate the boundaries of low-level primitives.

The Gestalt structures that are concerned with figure perception rather than low-level grouping are also found to produce a limited set of image features. The principle of good continuation states that the interpretation of smooth continuous lines is preferred over that of abruptly changing structure, whilst the principle of closure states that closed, or bounded figures are preferred over open figures. Primitives which are bounded into closed regions are manifest as localised structures in which image pattern on one side of the midline of the structure has some corresponding structure on the other side. These are both reasonable interpretations of ambiguous data in that they are the most likely to correspond to object structure, given that objects are necessarily bounded and tend to be elongated along at least one axis. Thus, elongation and boundedness are preferred interpretations and also good indicators of the presence of object structure in an image.

Other Gestalt principles can be viewed as being similarly related to the typicality of the visual scenes we deal with in everyday life. The principle of relative size states that all other things being equal, the smaller of two groups will be interpreted as a foreground structure. Given that objects tend to be localised parts of scenes and are of necessity smaller than the background in which they are set, the principle of relative size is likely to be a successful means of identifying bounded, object related structures in images.

However, each of the Gestalt principles outlined above describes only a very simple spatial structure, and whilst these may be associated with object properties, it is unlikely that any individual principle provides an adequate characterisation of general object structure. Where possible, it is desirable to avoid any criterion based method for assessing the importance of any single feature, as there is little reason to suppose that a "Gestalt template" would have any better success at capturing the complex and variable content of natural images, than high-level object templates or lower level edge, or surface templates. One consequence of the variability of natural images is that the criteria for segmenting a particular image in a particular way may depend strongly on local context. An object may give rise to some, but not other, of the image features, or it may give rise to poorly defined image features. For this reason it is desirable to use as few predetermined feature specifications as possible and to maximise the information content of features where they exist. One method for doing this may be to combine a number of abstract grouping principles into a single object description. An object description which looks for regularity along a number of dimensions should be relatively robust in the absence of one or more of these. Moreover, the presence of regularity on a number of dimensions may compensate for variability on any one of these. The regularities identified as potentially important for describing the generalised properties of objects include consistency, elongation, boundedness and localisation and structural regularity such as parallelism and alignment.

2.4 Symmetry as a compound Gestalt: Gestalt as generalised symmetry

The word symmetry comes from the Greek "in proportion" (*Collins English Dictionary*, 1986), and this definition suggests a global structure comprised of different parts in a single proportional relationship. There are many pattern types which come under this definition (e.g., bilateral symmetry, translational symmetry, rotational symmetry, dilational symmetry, temporal symmetry and others). In all of these the symmetry arises where one part of a pattern belongs with, and is localised with at least one other part. The proportions in the pattern are determined by the transformation used to create or describe the pattern and where the proportions are known, these precisely specify the spatial relations in the pattern. For example, bilateral symmetry is determined by the equal and opposite distance of matched pattern elements from the axis and this relationship determines the global regularity in the pattern. In bilateral symmetry, matching pattern primitives will be identical and therefore of uniform contrast. Each symmetric point pair can be thought of as a single elongated structure. These elongated structures are perfectly parallel, and aligned on the axis of symmetry, which lies exactly midway between the point pairs. Symmetric patterns have a tendency to appear as bounded structure with a distinct symmetry axis. Bilateral symmetry may therefore be a particularly expedient indicator for grouping under conditions of uncertainty because it combines a number of the Gestalt laws in a non-rigid fashion. Symmetric structure yields a complex spatial structure in which spatially separated parts are drawn together. The five Gestalt principles of similarity, proximity, good continuation, closure and relative size are manifest in images as localised regions of consistent contrast which will tend to be elongated, or reflected.

The term 'generalised symmetry' is used in this thesis to describe a pattern structure which is not necessarily perfectly symmetric, but which will produce pattern features which are characteristic of those produced by perfect symmetry. Generalised symmetry may be comprised of all, or only some of the pattern components of perfect symmetry. It is presumed that the structure will be stronger where more of these are present. Thus, repetition (or translational) symmetry has the components of elongation, parallelism and orthogonality, despite not having the constant reflected relationship across a single midline axis. There is a new constant relationship which is described by the equal distance between all dot pairs. Parallelism without symmetry or repetition does not have a constant relationship between paired elements, but has the components of elongation and orthogonality. Approximations to symmetry can be described in this kind of qualitative way rather than by quantitative description.

3

GENERAL METHODS

3.1 Overview

The purpose of the series of experiments reported here was to determine whether human observers sensitivity to symmetry is attributable to the pattern features of consistency, elongation, boundedness and regularity which were described in Chapter 2 as sufficient for representing global symmetric structure.

The intention of the general method was to determine visual systems' sensitivity to symmetry under a range of given conditions. The sensitivity measure used was the subjects' detection performance under conditions of increasing noise disruption of the symmetric pattern. The technique of adding noise to a pattern has been used previously to estimate the visibility or reliability of the pattern information by Barlow and Reeves (1979), who described the technique as a method for determining the resistance of the detection mechanism to dilution of the pattern.

In the experiments reported here, the stimuli were comprised of discrete pattern elements. The signal and noise elements were visually identical and the signal was carried only in the property of pairedness between elements. The detectability of this property was measured under a range of experimental conditions and the resulting changes in detection performance were examined. Performance differences as a function of experimental condition were analysed both quantitatively, in terms of absolute threshold differences and qualitatively, in terms of the shape and slope of the underlying psychometric function. From the threshold differences it is possible to ascertain which conditions affect performance and the magnitude of the effect, however the more detailed qualitative analysis of the changes in psychometric functions across condition allows some further insight into the effect of experimental conditions on the visual mechanisms employed in symmetry detection.

3.2 Method

3.2.1 Equipment

The stimuli were both generated and presented on a Macintosh Centris 650 computer with a colour monitor of screen size 23.5 by 16.5 cm (640 by 450 pixels) and refresh rate of 80 Hz. The screen was viewed binocularly with natural pupils and a free head position, at a distance of either 1 or 4 metres. The ambient lighting was fluorescent office lighting under which the background screen luminance was 30 cd/m2.

3.2.2 Stimuli

The basic stimulus comprised a square stimulus window containing symmetrically matched and uncorrelated elements at a range of signal to noise ratios.

Two element types were used in the experiments. These were small black dots of side 6 pixels subtending 0.12 degrees of visual angle (luminance 7 cd/m2) and larger variable discs ranging from 4 - 12 mm in diameter (0.06 deg and 0.18 deg at a viewing distance of 4 metres) and ±120 grey levels (luminance ranging from 7 - 60 cd/m2). Disc size and intensity were related such that the smaller discs occupied the extreme ends of the intensity range although the sign of the contrast was random.

Different viewing distances were used for the dot and disc displays. The dot displays were viewed from a comfortable viewing distance of 1 metre, whilst the disc displays were viewed from 4 metres. The purpose of this longer viewing distance was to prevent subjects from explicitly point matching disc position, as the individual discs were not clearly delineated at this distance, thereby forcing them to view the displays more globally. Further details particular to experiments are given in the individual method sections.

The stimulus windows measured 200 pixels along each side, subtending a visual angle of 4.6 degrees at a viewing distance of 1 metre and 1.15 degrees at a distance of 4 metres. In some of the conditions the stimulus windows were embedded in larger background windows measuring 300 pixels along each side which subtended a visual angle of 6.9 degrees at a viewing distance of 1 metre and an angle of 1.7 degrees at a distance of 4 metres.

In all experiments the density distribution of the dots was uniform across the stimulus field so that the presence or location of the target would not be cued by dot density cues.

Generating the patterns

The symmetric patterns were generated by reflecting a random distribution of dots about the vertical midline of the distribution. Constraints on the distribution of the signal dots are described in the individual methods sections. Except where axis orientation was explicitly manipulated, a vertical axis orientation was used in all experiments in order to control for the effect of axis orientation on detection performance.

Adding the noise

The noise elements in the experiments were identical in form, size and grey level to the signal elements. The noise dots were distributed in random positions across the stimulus window, subject to experimental constraints which are described in the individual methods sections. The noise dots were restricted from overlapping with any other dots.

3.2.3 Subjects

The subjects were recruited from a variety of sources. The author (TMC) was an experienced psychophysical subject and served in all of the experiments. Of the others CBH, a paid subject was experienced at a variety of psychophysical tasks but unaware of the purpose of the experiments. HEB, BMM, LJM, LAW, BPA, MB were naïve subjects recruited via the Stirling University psychology department subject panel and received course credit for participating. LDG, JAJ, and FC were volunteers recruited from the Psychology department and were unaware of the purpose of the experiments.

3.2.4 Procedure

The data that are collected in all the experiments to be reported below all have a similar form and are all analysed in the same way. Subjects were shown two displays, one containing a target plus some noise and one containing just noise. The two stimuli were presented in sequence, for 1 second each. Each stimulus was pre- and post- masked by a white noise mask in order to eliminate any persistence of the image. The mask was shown for 250ms, and this provided an adequate delay between stimulus presentations. Subjects were asked to indicate which display contained the target by pressing one of two mouse keys. Subjects were given a brief practice session to familiarise themselves with the task. Symmetry detection performance is found not to change qualitatively with subject sophistication (Barlow and Reeves, 1979; Royer, 1981; Wagemans et al, 1991), therefore, long practice runs were thought to be unnecessary and no feedback was given between trials. Unless specified, all trials were blocked by experimental condition. The two experimental conditions of fixed and variable axis position, which are present in all experiments were tested in random order. Subjects completed 3 experimental runs of 64 presentations for each condition.

From trial to trial, the number of elements in the target was varied in proportion to the noise, and detection performance was measured as a function of this parameter. An adaptive method of constant stimuli (APE; Watt and Andrews 1981) was used to select informative signal to noise ratios (SNRs) on the psychometric function. APE generated a range of stimulus levels between 0 and 100 which correspond to a range of SNRs. At an APE level of 100 a target stimulus containing only signal dots is presented, and the subject is expected to perform at 100% correct level. At an APE level of 0 the target stimulus contains only noise dots. At this level the discrimination task is impossible and the subject is expected to perform randomly. APE presents the range of stimulus levels in a pseudo-random sequence which is influenced by the subject's response patterns. The range of stimulus levels are interleaved within a run of 64 trials, however the selection of stimulus level is not entirely random as APE samples most heavily at those points on the psychometric function where the subject's performance changes most rapidly. For each experimental condition was determined from a single psychometric function obtained from combining the data from 3 separate runs.

3.3 Psychometric Functions

Performance, expressed as the number of times that subjects chose the correct patch, was measured as a function of the number of target elements. Psychometric functions can be generated from this data. These have variable slope, in that the rate of change of performance as a function of stimulus level varies with condition, but they also have variable shape. This is unusual: normally psychometric functions can be described by changes in just one parameter, usually referred to as the threshold. In the present experiments, it is necessary to consider both a threshold derived from the psychometric functions, and the overall shape of the function.

Standard curve-fitting procedures (quasi-Newton and simplex) were used to fit the data to a general form of psychometric function. It is normal to use a cumulative Gaussian function for these purposes and to estimate up to three parameters, namely the mean and standard deviation of the underlying error distribution and, if necessary an exponent to which the stimulus level is raised (see Watt, 1991 for a full rationale). The psychometric function relates the probability of a positive response to the stimulus level t and is given by:

$$P(R+,t) = \int_{-\infty}^{t} \exp\left(-(s/\sigma+\mu)\right).ds$$

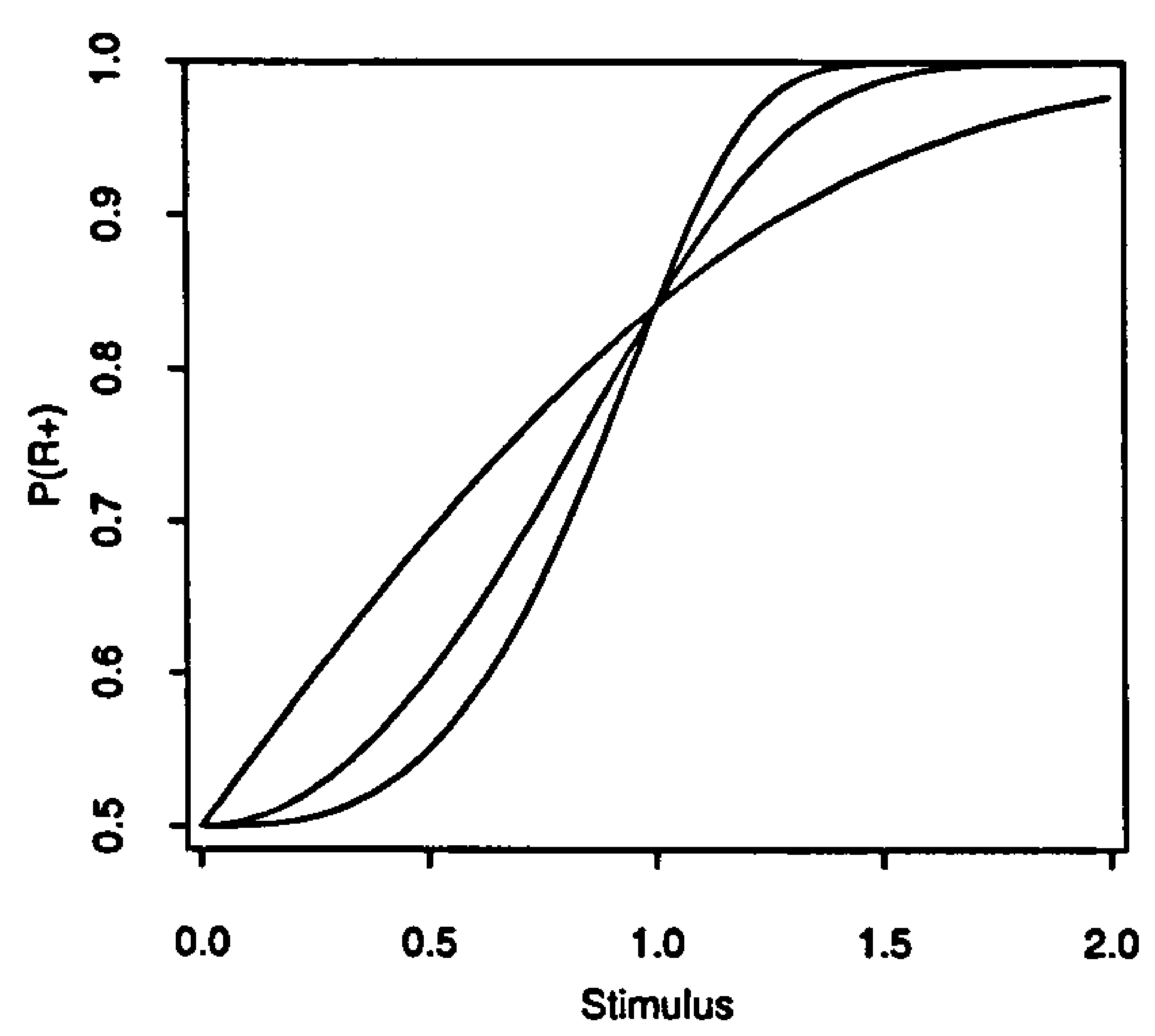
where μ is the centre of the psychometric function, and σ is its slope. In order to allow the shape to vary, the stimulus level is raised to some power, α, taking care to preserve the stimulus level sign:

$$P(R+,t) = \int_{-\infty}^{t} \exp\left(-\left((s/\sigma)^{\alpha}+\mu\right)\right).ds$$

Thus there are three parameters to estimate from the data. Of these, there is no reason to suppose that the mean μ will vary and this was simply assumed to be zero in order to render the curve-fitting process more stable. Despite this simplification, good fits were always obtained, generally explaining over 90% of the variance in the data.

It is convenient to use the σ term as a threshold in this expression. This corresponds to a level at which subjects are responding correctly on 83% of trials. Figure 3.1 shows a family of psychometric functions all having the same value for σ but each having a different exponent α. These functions all cross at the 83% point, and thus it can be seen that σ is a suitable measure of threshold that is independent of shape.

Figure 3.1



Statistical tests of significant differences between psychometric tests

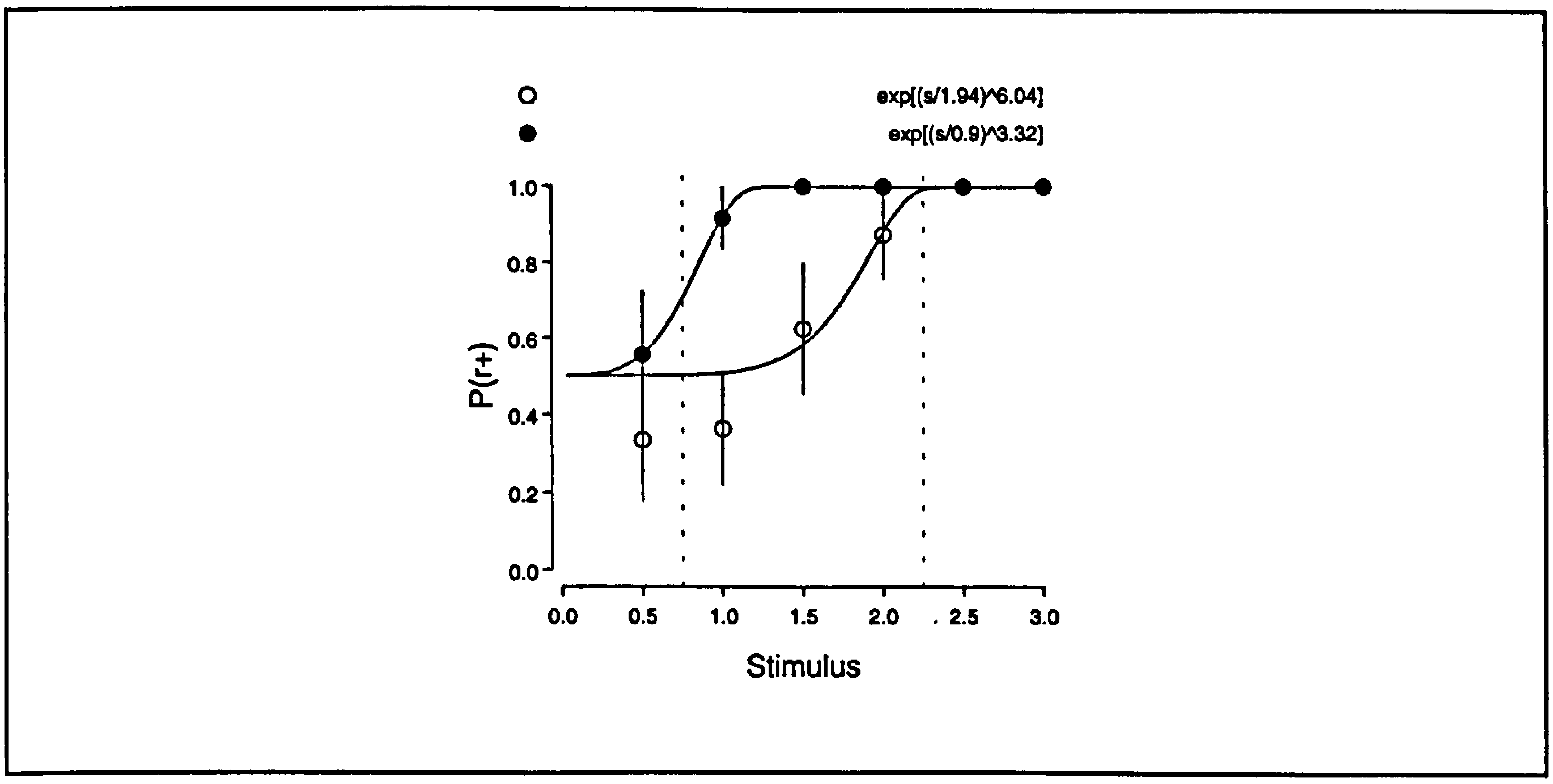
The method adopted for testing the significance of any difference between two psychometric functions is described. The basis for the test is to take all the trials between two arbitrary points on the stimulus dimension and calculate the number of correct responses within this range for each psychometric function.

Within a selected stimulus range, there are two numbers of trials (n1 and n2) and two counts of correct responses (t1 and t2). It is then possible to calculate the probability that the two binomial samples t1 out of n1 and t2 out of n2 could be drawn from the same distribution. This is done with a Pearson's Chi-Square statistic, using (t1+t2) out of (n1+n2) as the expected counts.

The stimulus range to use is assessed by a search process. Within the total range of stimuli tested, all possible starting and end points for the stimulus range are tested, and that range with the most significant difference is taken as the range. Since most of these tests are highly correlated, this does not significantly bias the test towards producing a significant difference. Independent tests applying this procedure to simulated psychometric functions has shown that the probability of recording a significant difference (with $p < 0.05$) for two runs from the same underlying psychometric function is 0.05 (Watt, personal communication). This indicates that the testing process is valid.

Figure 3.2 shows two different psychometric functions, found to be significantly different ($p = 0.0017$). The vertical dashed lines show the range of stimulus values over which this difference was found.

Figure 3.2



4

SYMMETRY DETECTION IN RANDOM DOT PATTERNS

4.1 Overview

The vast majority of research on symmetry perception has employed the random dot pattern as a vehicle for studying the perception of symmetric structure. In many of these studies the aim is to conduct a detailed investigation of the perceptual components of symmetric structure. The general approach is to isolate symmetric structure from context and meaning by using random patterns, and then to study the effects of various stimulus parameters on detection of symmetry, for example the effects of positional jitter on the elements, the effects of orientation, the effects of disrupting midpoint collinearity, the effects of proximity of dots to the midline axis, etc.

The approach taken in this thesis is slightly different, as the broad aim of this work is not to investigate the effects of carefully defined parameters on the perception of symmetric structure, but to investigate the role of symmetry *per se* on early visual processing and image segmentation. In order to do this it is necessary to view symmetry perception in a wider context than is provided by the method described above.

The study of symmetry perception in the context of more general visual processing requires that careful consideration be given to the kind of stimuli used in experimentation. For example, it cannot be assumed that the random dot pattern is an ideal stimulus type for this kind of investigation. Our natural visual environment is not comprised of randomly positioned elements, but is ordered in ways that may be exploited by early visual mechanisms. Neither the order nor the mechanisms are fully understood and theories of these have been expressed in different ways. For example, Gibson (1966) proposed that perception is enabled by invariant properties of objects and surfaces in the external world. Marr (1982) invokes low-level, general reflectance properties of surfaces in the physical world and the correspondences which exist between these, whilst Watt (1988) discusses the general constraints on surface properties which allow the interpretation of luminance cues in terms of external physical features. For the moment, the precise nature of these physical constraints is irrelevant. What is important is that early visual processes such as segmentation and grouping are facilitated by an order, or organisation on the visual input, which is imposed by constraints on the makeup of the physical world.

There is a danger in using artificial stimuli to investigate general visual processes, which is that these stimuli are not necessarily subject to the constraints imposed by the physical world. As a result, artificial visual tasks may not exploit the mechanisms which operate in natural visual processing. Moreover, the detection strategies used by subjects in artificial visual tasks may be specific to the stimuli used and unable to generalise to other situations.

It is therefore important to establish the appropriateness of dot stimuli for the study of low-level pattern processing. Random dot patterns are not homogeneous stimuli, but a class of stimuli, within which a great deal of variation is possible, therefore it is necessary to establish the effects of a variety of stimulus configurations and presentation conditions which have hitherto rarely been controlled across studies on symmetry perception.

The idea that relatively subtle differences in the construction and presentation of basic random dot stimuli can have marked effects on detection performance is central to the first two experimental chapters of this thesis. In order to tease out these effects it is necessary to establish the relative contributions of the different sources of structural information in the stimuli. The purpose of this series of experiments was to systematically test symmetry detection in random dot patterns under a range of conditions in order to determine the cues which need to be present.

4.2 Experiment 1 - Symmetry detection in a ‘basic’ random dot pattern

4.2.1 Introduction

The aim of the first experiment was to determine a baseline level of performance in a symmetry detection task with stimuli similar to the basic stimulus used in Barlow and Reeves (1979).

4.2.2 Method

Stimuli

The stimuli were square field random dot patterns composed of 200 small identical dots (see General Methods in Chapter 3 for details). The target stimuli contained varying proportions of symmetric and random (noise) dots. The symmetric dots were laid first, followed by the noise dots which occupied the remaining spaces between the target dots. The only constraint on dot position within the stimulus window was that dots should not overlap. The distractor stimuli contained only noise dots. The stimuli were presented in a fixed position in the visual field and the axis was always vertical. Sample stimuli are given in Figure 4.1.

Subjects

The subjects in this experiment were TMC, CBH, and PBA (see General Methods for subjects' details).

Task

The subject's task was to indicate which of the two stimuli presented on each trial contained the symmetric stimulus. Subjects were shown a number of sample stimuli to explain the task, which made clear the position and orientation of the axis.

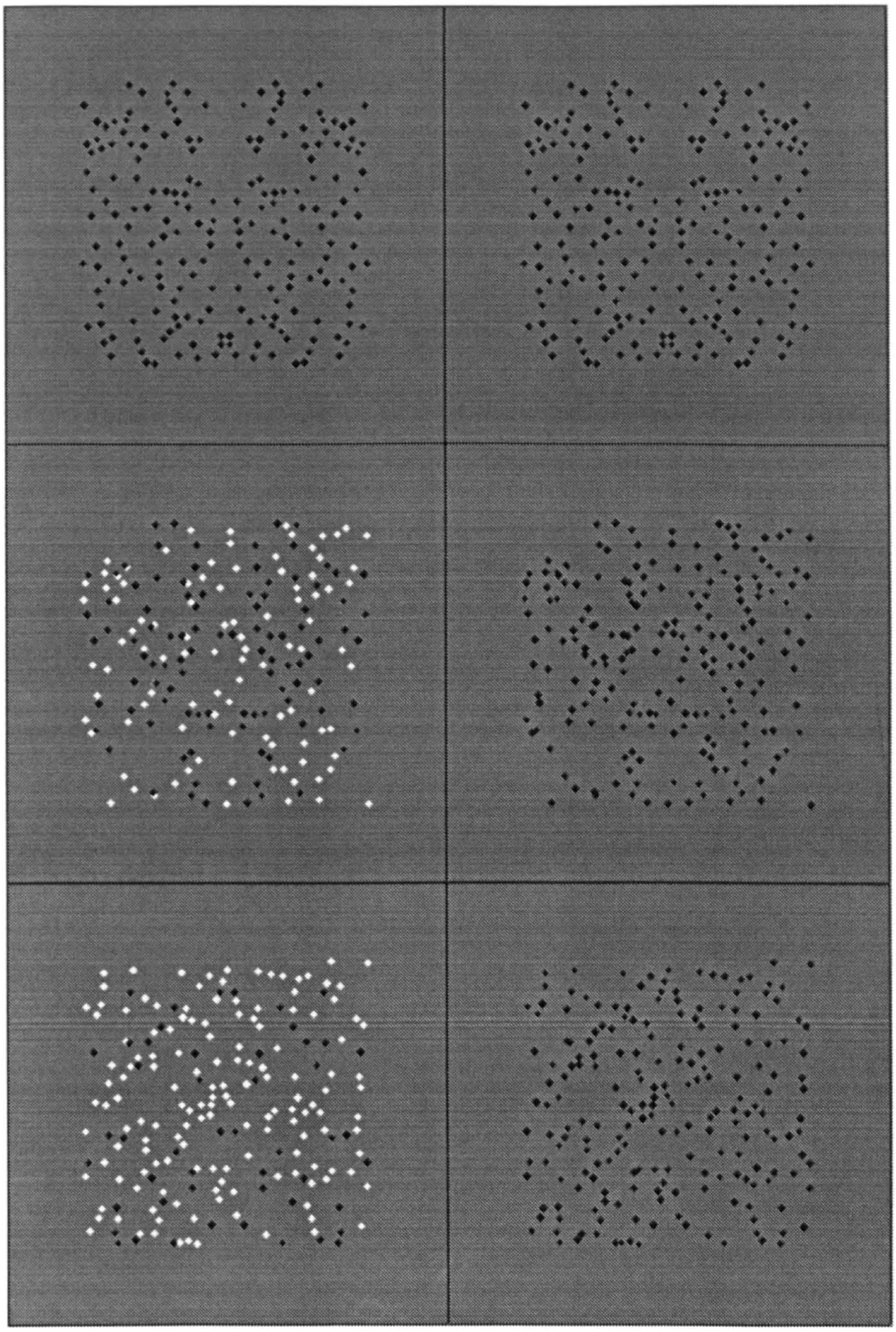


Figure 4.1. An example of the random dot symmetry pattern used in Experiment 1. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the noise dots are shown in white and the symmetric dots in black. In the right hand column, the stimuli are as presented to the subjects. It can be seen that as SNR decreases, the density of the signal dots is reduced, as is the probability of close matches occurring.

4.2.3 Results

Figure 4.2 shows the psychometric functions obtained from the three subjects on this task. The psychometric functions obtained show that perfect discrimination is achieved at full signal and is sustained at moderate levels of noise interference, beginning to deteriorate below around 60-80% signal. Performance deteriorates smoothly for two of the subjects, less so for subject CBH. Chance performance is reached at around 15-30% signal for two subjects, however, this is higher for subject CBH, whose performance deteriorates more quickly, reaching chance at around 50% signal.

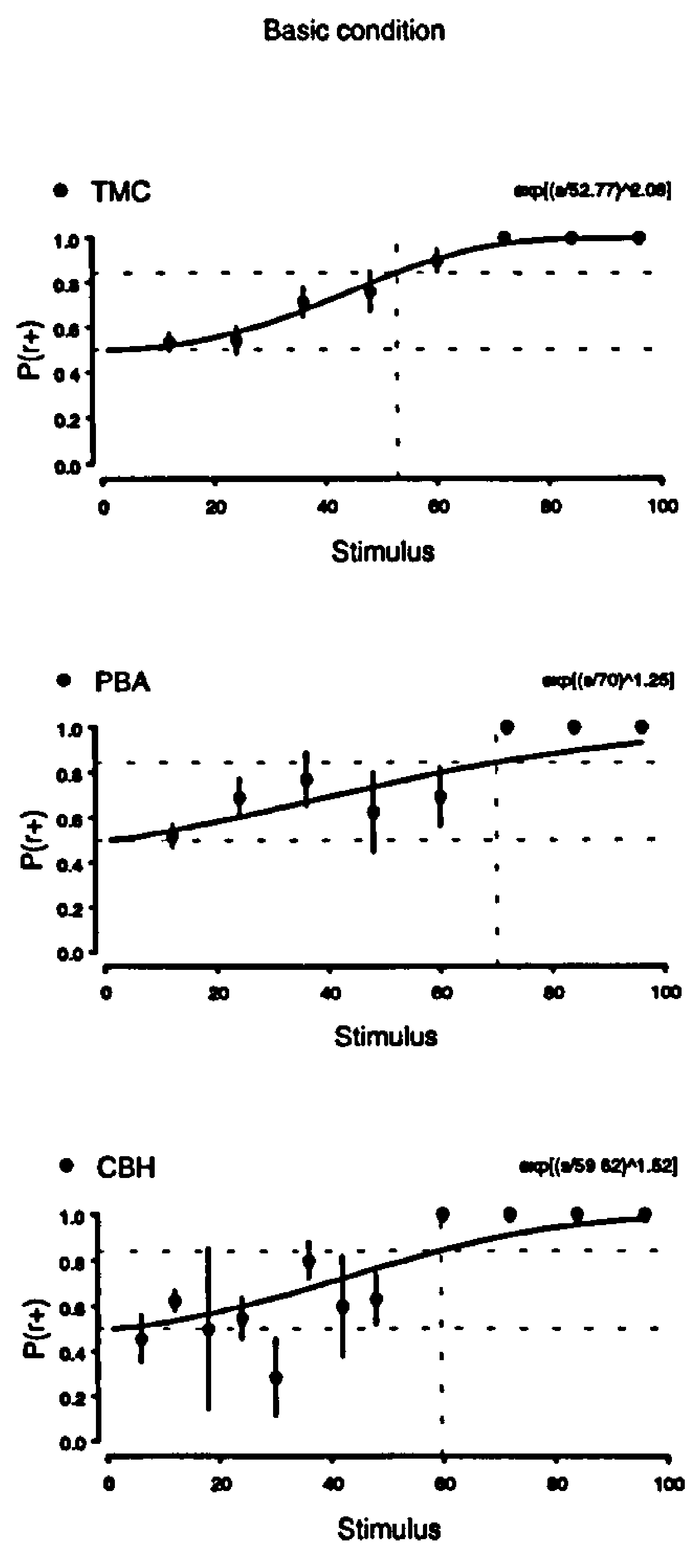


Figure 4.2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

The data from this experiment are summarised as detection thresholds in Figure 4.2. which shows that the detection thresholds obtained from three subjects range between 52 and 70 % signal across subject. For this task, the subjects require between 52 and 70 dot pairs out of a potential 100 pairs to detect symmetry at threshold.

4.2.4 Discussion

The pattern of performance found in this experiment is that of perfect discrimination at full signal, initially sustained across moderate levels of noise interference, followed by a steady decline in performance as noise is increased.

These discriminability functions are similar to those obtained by Barlow and Reeves (1979, Experiment 1), who also reported a smooth change in performance across the stimulus range with a shallowing of the function at the higher stimulus levels. Barlow and Reeves tentatively suggest that this shallowing may be due to the fact that at the higher stimulus levels, the position and orientation of the axis are well defined in the stimulus. Beyond the cue level at which this definition emerges, a lesser advantage would be expected from the increase in signal to noise ratio. In other words there is a level at which the global symmetric shape emerges in the dot pattern and this global shape gives strong definition to the axis. This is a plausible interpretation of the data, but one which invites further investigation. The reason for this is that in the Barlow and Reeves experiment, the position and orientation of the axis was implicitly defined by the parameters of the stimulus, in which the axis was centrally fixed with respect to the observer and was always vertically oriented. It is possible that a given knowledge of the axis position and orientation changes the nature of the task, from one which requires that the symmetric region be located by the subject, to one which allows a highly local, systematic testing for structure about a predetermined axis with no reference whatsoever to the global symmetry in the pattern. When making claims about the contribution of global pattern properties to detection performance, it is very important to ensure that a local detection strategy such as this is not available to the subjects.

In order to determine precisely which cues the subjects are using to detect the symmetry, it is important not simply to describe the patterns of performance across the stimulus range, but also to interpret these patterns of response in terms of the stimulus content. By establishing those stimulus factors which change as signal to noise ratio is varied, it may be possible to isolate the precise determinants of subjects responses and thereby determine the essential perceptual components of symmetry.

It is not intuitively obvious what the essential components of symmetric structure may be, however the results of this first experiment provide some general pointers. The detection thresholds found in this experiment are somewhat higher than the threshold of 30-40% signal reported by Barlow and Reeves and there are no immediately obvious reasons why this should be the case. Although the stimuli were not identical to those in the Barlow and Reeves experiment they contained essentially the same components of random dots reflected across a fixed midline axis. That a difference in detectability was found between the two patterns, implies that the essential perceptual components of symmetric structure may not be contained solely in the symmetry relationship between individual point pairs (i.e., the point pair matches) which are present in all symmetric patterns. Rather the detectability of a symmetric pattern may depend on the relationships which emerge between the pairs of symmetric dots (i.e., the multi-local cues which emerge from clusters of paired dots). The detectability of these more complex relations may vary widely amongst different types of dot pattern, depending on the number of dots in the pattern, the density of the dots, the size of the dots, the presence of noise etc.. Such stimulus factors may therefore differ between studies which use the random dot stimulus in symmetry research. It is therefore important to ascertain whether these rather subtle differences between different types of random dot stimuli have an effect on performance overall, and in particular whether the detection strategies used by the subjects are peculiar to certain stimulus types.

The overall conclusion from this experiment is in general agreement with that of Barlow and Reeves in that symmetry detection is found to be a graded, rather than a discrete, all or nothing property. However it is necessary to extend this description into an investigation of the perceptual components of symmetry. This can be done by establishing the cues which subjects use to detect the structure.

To begin to determine what the important cues to symmetry might be in these stimuli, the pattern contour and axis information were dissociated in Experiment 2 in order to establish the relative contributions of these two sources of information to symmetry detection. This was achieved by selectively disrupting the outline of the stimuli, leaving intact the fixed axis position and the internal symmetry in the pattern.

4.3 Experiment 2 - The effect of removing outline cues on symmetry detection in random dot patterns.

4.3.1 Introduction

The purpose of this experiment was to determine the effect of pattern outline information on subjects' performance in a detection task. Pattern outlines were disrupted by the addition of a random dot surround to the stimulus, which concealed the edges of the symmetric pattern.

4.3.2 Method

__Stimuli__

The stimuli were similar to those in Experiment 1. In this experiment however, the stimuli were embedded in a larger surrounding window. This surrounding window measured 300 by 300 pixels and contained an array of random dots which were distributed between the stimulus window and the surrounding window, forming a noise surround to the stimulus. The stimuli (and therefore the target axis) were presented in a fixed central position within the surround window.

Dot density was uniform across the whole display and there was no discernible borderline between the stimulus and background dot patterns. Changes in the proportion of signal to noise dots occurred only within the 200 dots in the stimulus window. The random pattern of background dots changed between trials, but remained constant in number. Sample stimuli are given in Figure 4.3.

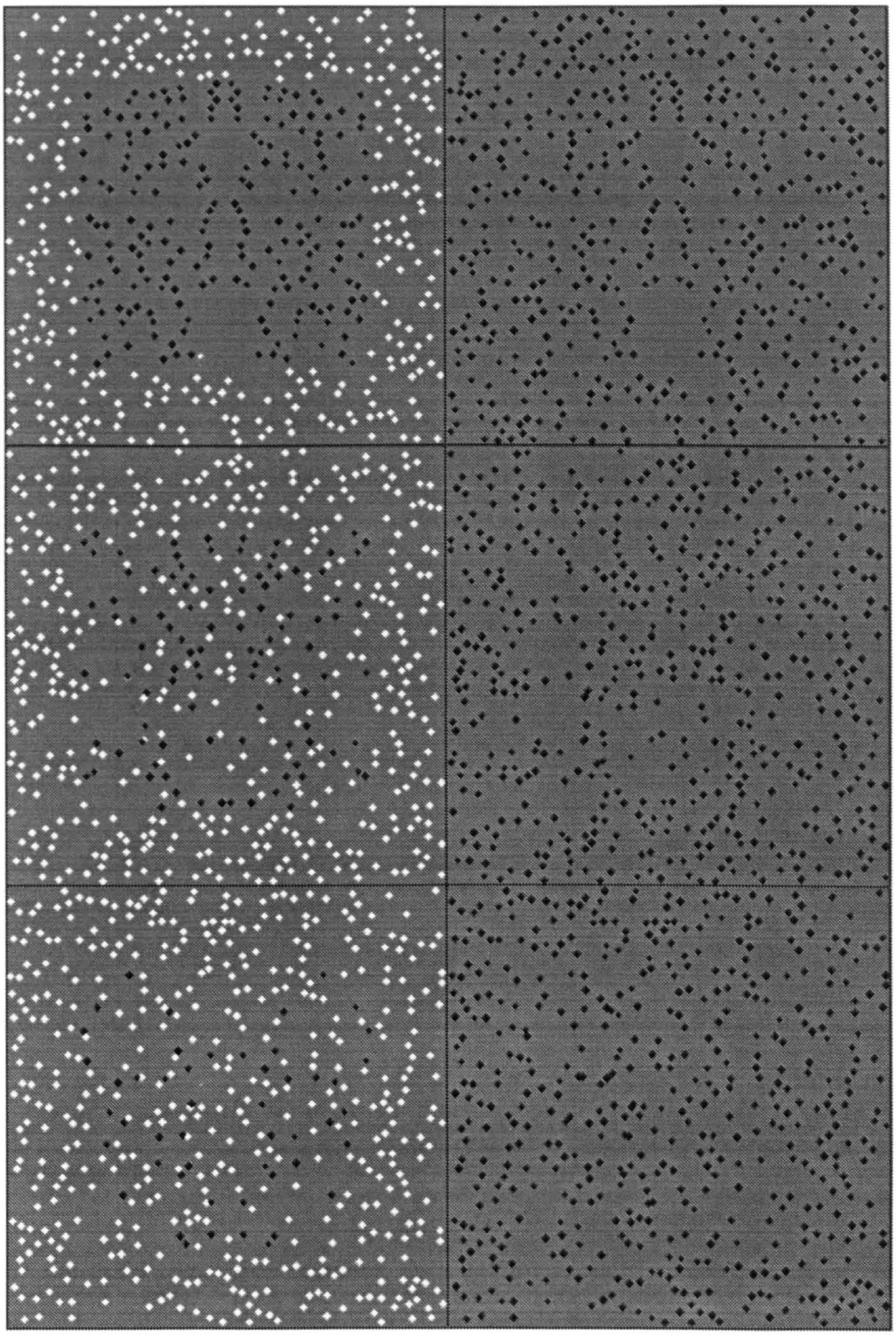


Figure 4.3. An example of the random dot symmetry pattern used in Experiments 2 & 3. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the noise dots are shown in white and the symmetric dots in black. In the right hand column, the stimuli are as presented to the subjects. It can be seen that any distinctive outline shape in the symmetric pattern is obscured by the noise surround. In Experiment 3 the position of the stimulus window was varied within the outer background window.

Subjects

The subjects in this experiment were TMC, LJM, and PBA (see General Methods for subjects' details).

Task

The subject's task was to indicate which of the two stimuli presented on each trial contained the symmetric stimulus. Subjects were shown a number of sample stimuli to explain the task, which made clear the position and orientation of the axis.

4.3.3 Results

Figure 4.4 shows the psychometric functions obtained from the three subjects on this task. The psychometric functions obtained show that with the exception of one data point from subject LJM, perfect discrimination is achieved at full signal and is sustained at moderate levels of noise interference, beginning to deteriorate below around 70% signal. Chance performance is reached at around 30 - 40% signal.

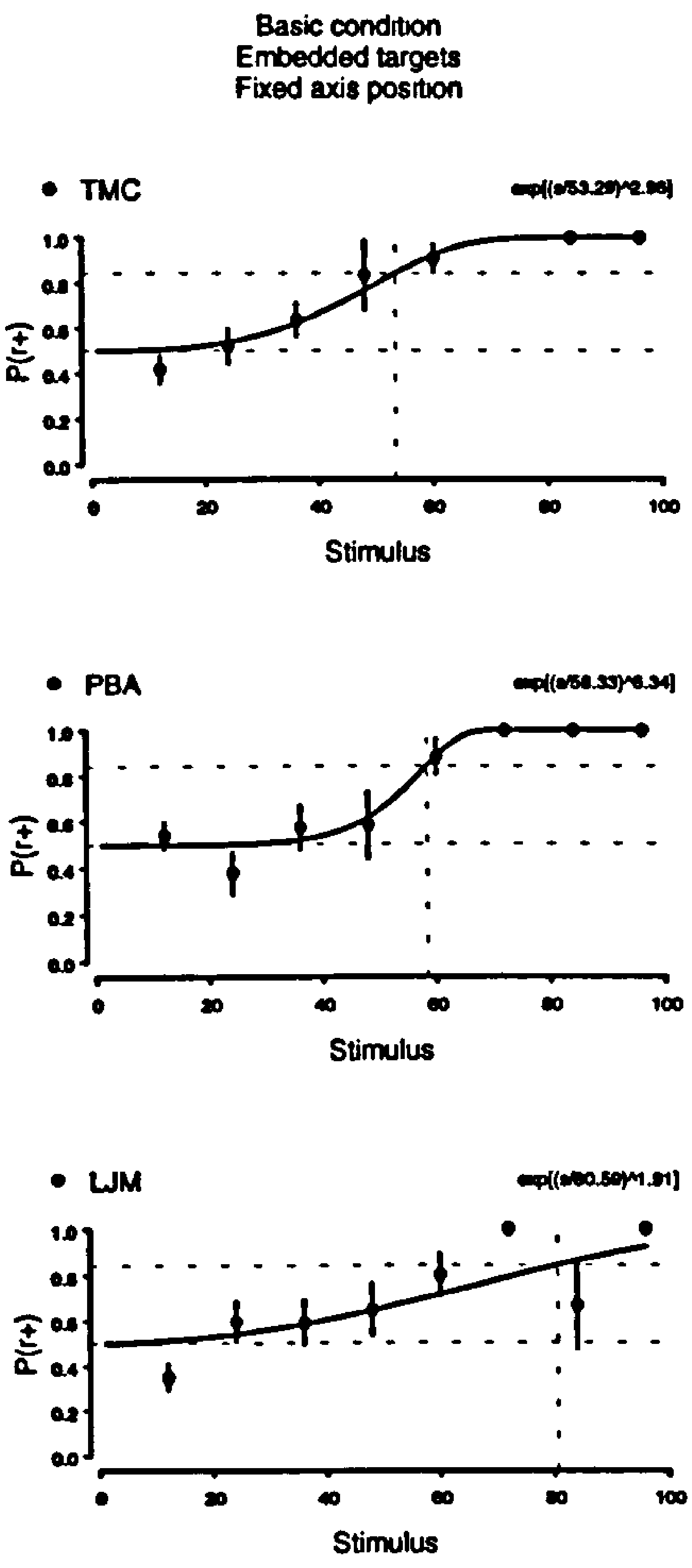


Figure 4.4. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

The data from this experiment are summarised as detection thresholds in Figure 4.4 which shows that the thresholds range between 53 and 80 % signal for three subjects. For this task, the subjects require between 53 and 80 dot pairs out of a potential 100 pairs to detect symmetry at threshold.

The data obtained in this experiment are compared with those in Experiment 1 to show the effects of removing pattern outline information in symmetric stimuli. Only two subjects completed both experimental tasks. A comparison of the psychometric functions obtained in Experiments 1 and 2 reveals no significant differences in performance, indicating that the removal of outline information has no effect on performance in this task.

4.3.4 Discussion

The effect of outline removal found here is slight compared with that of Wenderoth (1995) who found that symmetry detection in dot patterns was significantly poorer when the patterns were embedded in a random dot surround. The stimuli in the Wenderoth study differed from those used here in that the symmetric patterns were fully symmetric and were not diluted by noise dots. The data in this experiment that are most directly comparable with those reported by Wenderoth are therefore those at 100% signal, and it can be seen that perfect detection performance was achieved by all subjects under both non-embedded and embedded conditions, both at full signal, and also with some added noise. The shorter presentation times used in the Wenderoth study (150 ms) may account for the discrepancy in results.

The absence of any large effect of outline removal suggests that the perception of 'object type' outlines such as butterflies and insects is not crucial to performance on this task. This does not necessarily imply that outline shape is unimportant in symmetry detection, and the lack of effect here may reflect the fact that there are other, highly salient cues to symmetry in the stimulus, which compensate for the loss of outline information. It has been suggested that imagable shape cues are advantageous under conditions such as skewing, where the symmetric relations between elements and axis are disrupted (Wagemans, 1990). It is possible then, that local symmetric relationships between elements around the axis are easily detected, particularly at the higher stimulus levels. It is noted above that the fixed axis position in these stimuli may provide a cue to symmetry, allowing a local solution to the detection task, in which only those dot pairs around the axis region are considered. A local solution is defined as that which involves only certain locally distributed pattern elements as opposed to the global symmetric pattern (Kimchi and Palmer, 1982).

For the purposes of this thesis it is important to determine the contribution of the axis cue to performance on a detection task, as one of the major concerns of the thesis is to identify those pattern types which can be detected without prior knowledge of location. Therefore, to test the extent to which detection is dependent on high-level knowledge of axis position, a further experiment was carried out in which the axis cue was disrupted by varying the position of the axis between trials.

4.4 Experiment 3 - The effect of axis positional uncertainty on symmetry detection in random dot patterns.

4.4.1 Introduction

In Experiments 1 and 2, the axis position was fixed and vertically oriented in all trials and therefore known to the subject. The purpose of the present experiment was to determine whether detection performance on this task relies on this external cue to symmetry.

Barlow and Reeves (Experiment 4) measured the effect of axis positional uncertainty by interleaving trials in which the axis was either centred or displaced to the right or left of the fixation point at a range of eccentricities. The results showed that symmetry was more difficult to detect and performance more variable under uncertainty of axis position than with a fixed axis. Nonetheless symmetric structure was still detectable in these targets.

The patterns of performance on Barlow and Reeves task may provide some insight into the detection strategies used by the subjects. Firstly, the degree of eccentricity had no consistent effect on performance. Moreover, no distinction was made between left and right displaced axes. Secondly, despite random interleaving of the three possible axis positions the subjects showed better performance in the central axis trials than in the displaced, suggesting that of the three possible axis positions subjects tended to test in the central position first. Although purporting to measure the effect of unknown axis position, the range of axis positions in this experiment were sufficiently limited to allow a discrete sampling strategy, therefore detection performance may still have been somewhat determined by the parameters of the stimulus, rather than by the salience of the symmetry itself.

The purpose of this third experiment was to determine the effect of axis positional uncertainty on symmetry detection performance in the absence of external cues to axis position. This was done by varying the axis position on each trial, allowing the axis a full range of movement within a restricted space. The axis orientation remained vertical on all trials. In order that the edges of the stimulus window did not provide a cue to the target position the stimuli were embedded inside larger background windows which contained uncorrelated noise dots. The position of the stimulus windows varied within the boundaries of the background windows between trials. In this experiment, the stimuli are both embedded and varied in position within the background window, therefore both outline and axis information are disrupted.

4.4.2 Method

Stimuli

The stimuli were identical to those in Experiment 2, comprising a stimulus window with varying proportions of symmetry and noise embedded in a background window with noise dots surrounding the stimulus (see Figure 4.3). The only difference was that the position of the stimulus window was varied randomly from trial to trial. Although the axis of symmetry remained vertical, the position of the axis was varied randomly between trials. The only constraint on the axis position was that it should allow the entire stimulus window to fall inside the background window.

Subjects

The subjects in this experiment were TMC, LJM, and PBA (see General Methods section for subjects' details).

Task

The subject's task was to indicate which of the two stimuli presented on each trial contained the symmetric stimulus.

Subjects were shown a number of sample stimuli to explain the task, which made clear the position and orientation of the axis well as the position of the stimulus window in the background window.

4.4.3 Results

Figure 4.5. shows the psychometric functions obtained from the three subjects on this task. Two subjects on this task show similar patterns of perfect detection between 100% and 70% signal, with performance declining rapidly to chance at 60% signal. The third subject in this condition shows more erratic performance, with no plateau of perfect detection and a more gradual decline in performance across the range.

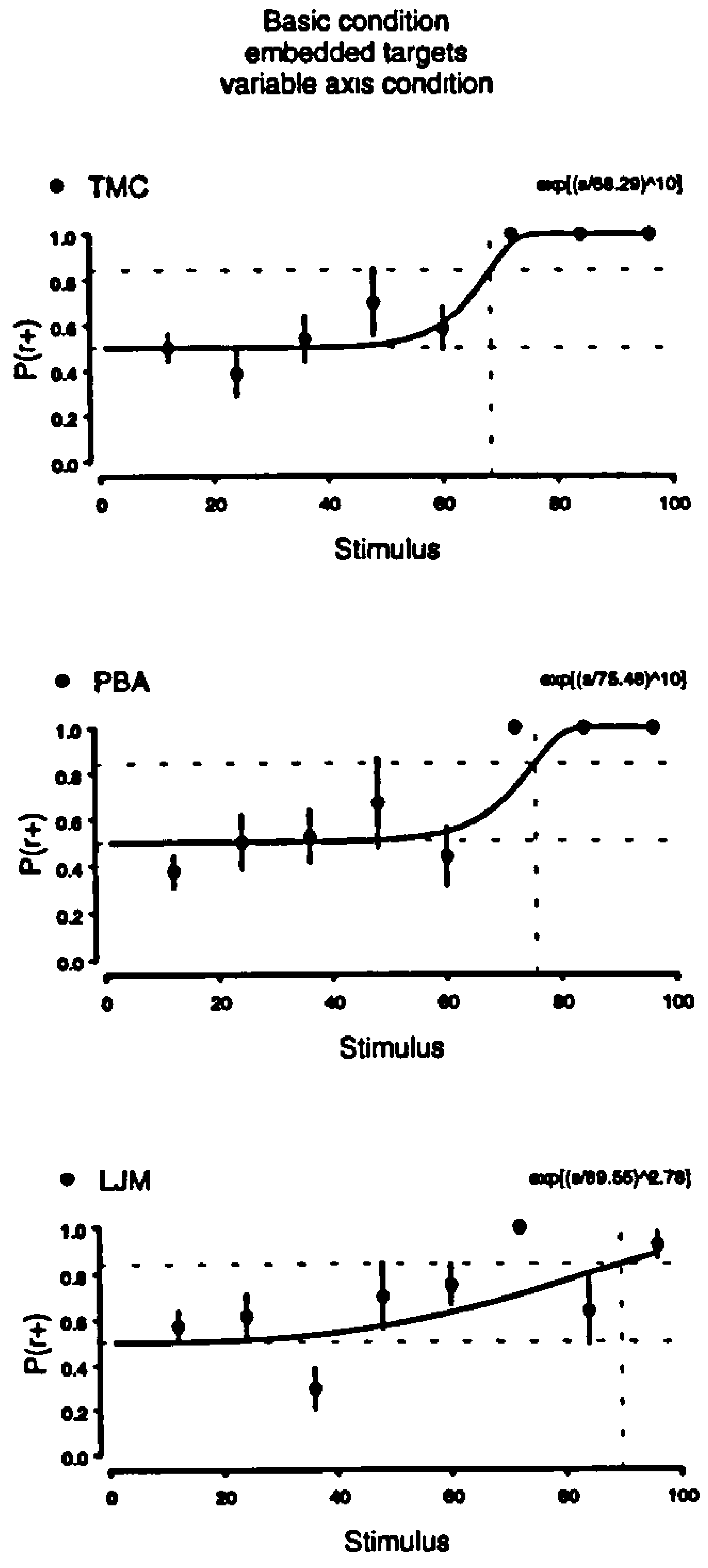


Figure 4.5. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

The data from this experiment are summarised as 83% correct detection thresholds in Figure 4.5. The thresholds obtained in this condition were between 68% and 89% signal.

The data obtained in this experiment are compared with those in Experiment 2 to show the effects of disrupting axis position information in symmetric stimuli. Data from three subjects were compared and detection thresholds were found to be increased for all subjects, however, only two subjects showed significantly poorer performance at the 60% signal level as a result of removing the axis cue (PBA, $p<0.001$; TMC, $p<0.008$).

4.4.4 Discussion

The effects of axis positional uncertainty on symmetry detection performance can be seen by examining the psychometric functions. These show that at the highest stimulus levels, symmetry is easily detected (for two of the subjects). Performance at the high stimulus levels is similar to that in the cued axis conditions, supporting Barlow and Reeves (1979) conjecture that the characteristic shallowing of the functions observed at these levels is due to the strong definition of the axis given by the pattern. There are strong cues to symmetry available at high stimulus levels, which are globally detectable and which do not necessarily rely on prior knowledge of the pattern position.

However, the effect of axis uncertainty becomes apparent in the psychometric functions below this point of perfect discrimination, as the functions decline steeply, falling to chance level almost immediately. That detection is sustained across a wider range of stimulus levels when the axis position is fixed (as in Experiments 1 and 2), but not when it is variable, suggests that axis position information cues the presence of symmetric structure at the lower stimulus levels where it cannot be detected globally. This result therefore supports the claim that a fixed axis position allows the use of a detection strategy which is not dependent on the perception of intrinsic pattern structure, but rather on highly reliable stimulus characteristics. The nature of this strategy is further investigated in Chapter 5.

4.5 General discussion

The possible role of outline information in symmetry detection is noted, but will not be considered further in this thesis. Of more interest here are the effects of axis information and changing signal to noise ratio (SNR), both of which had a considerable effect on performance.

4.5.1 The effects of changing signal to noise ratio.

The most superficial change which occurs as SNR decreases is that the absolute number of signal dots falls and the number of noise dots increases proportionally. It is possible that performance varies as a function of the absolute number of signal dots present in the stimulus.

However the number of paired dots present may not be the strongest factor in determining detection ability. A change in the SNR causes a number of related changes in the stimulus (see Figures 4.1 and 4.3 for illustration). Firstly, it adjusts not only the relative proportions of signal to noise but also the relative densities of the signal and noise dots. As the cue size decreases, fewer signal dots are distributed over a constant window area therefore the signal dot density decreases as cue size decreases.

A further effect of decreasing the signal to noise ratio is that the probability of dots falling close to the axis region is reduced.

Finally, as the number of signal dots is decreased, dilution of the symmetric signal is increased proportionally. Detectability may depend not only on the level of signal present in the stimulus, but also to the degree to which this is diluted by noise dots.

Because these factors covary, it is not clear whether all of these factors are important determinants of detection performance, not is it clear which of these factors interact with prior knowledge of axis position. However, some such interaction between axis knowledge and internal stimulus factors might be expected.

4.5.2 Global cues

Where no axis position information is available it can be assumed that subjects are using some sort of global strategy to detect the stimulus. This depends not on the perception of point pair matches, but on the relationships between dot pairs (i.e., dot clusters). A detection strategy which depends on the relationships between matched pairs will begin to break down as the density of the signal dots is reduced, as the components become increasingly disparately arranged and are broken up by random noise interference. Global relations are therefore likely to be dependent upon the density factor.

4.5.3 Local cues

Axis position knowledge confers a detection advantage. Given axis knowledge, symmetry can be detected where it otherwise cannot and this may be due to a particular detection strategy of searching for closely matched dot pairs in a very narrow region of the stimulus around the axis position. However, local information varies with signal to noise ratio and whilst symmetric matches have an equal probability of occurring at any distance from the axis and at any point along the length of the axis, the probability of a match occurring in a particular region will decrease as signal dot density is reduced. Therefore, the probability of a match occurring close to the axis decreases as signal to noise ratio is decreased, making a highly local strategy unreliable at lower signal to noise ratios.

4.6 Conclusion

The results of Experiments 1-3 indicate that a variety of cues may be used in symmetry detection, which interact with SNR. However, these experiments do not discriminate between the different sources of information described above, which are a function of SNR, for the reason that all of these factors co-vary in Experiments 1-3 such that the local and global cues are always strengthened simultaneously.

Further investigation is required to determine the nature of local and global cues to symmetry and the circumstances under which detection strategies based on these may be optimal.

5

EFFECTS OF DENSITY AND NOISE IN SYMMETRY DETECTION

5.1 Overview

The finding of the 'basic' symmetry detection task in Experiment 1 is in broad agreement with Barlow and Reeves first experiment — that symmetry detection is a graded, rather than a discrete task. It might have been assumed from the smooth change in performance found in Experiment 1, that a steady decrease in stimulus level, produces a corresponding decrease in signal along a single continuum, however, the results of Experiments 2 and 3 do not bear this out. Detection performance declined slightly, but not significantly with the removal of outline shape. It deteriorated more seriously with the additional removal of axis information, suggesting whilst outline and axis cues both contribute to symmetry detection, and can be used somewhat independently, the axis cue contributed most to the detection performance found in Experiment 1. The fact that symmetry can be still detected in the absence of both axis and outline cues, indicates that there are other cues to symmetry available which change with stimulus level and which appear to break down at around 60% signal. Also of interest was the finding that a decline in performance due to stimulus condition did not occur with a fully symmetric stimulus but only as a function of decreasing SNR. The available cues to symmetry appear to be useful to different extents across the stimulus range and are used in conjunction to sustain performance across a wide range of stimulus levels. Thus, a change in the signal to noise ratio produces a quantitative change in the information in the pattern, and also a qualitative change in the stimulus content. Changing the signal to noise ratio does not continuously alter the value of a unitary variable, but rather adjusts the values of a number of variables or cues.

To identify these cues to symmetry it is necessary to separate the perceptual effects of a number of stimulus factors which alter simultaneously with a change in SNR. By separating these stimulus factors and testing their effects independently in a range of experimental conditions, it may be possible to arrive at a set of stimulus conditions which are sufficient for presegmental symmetry detection.

The purpose of this series of experiments was to begin to dissociate the effects on symmetry detection of four stimulus factors which change with SNR. The factors of interest were absolute number of signal dots, density of signal dots, probability of close matches and the effect of stimulus dilution by interposed noise dots on the targets. The effects of contour and axis cues were measured as a function of changing SNR under conditions which dissociate these stimulus factors.

In this experiment the effects of signal dot density were dissociated from the effects of absolute number of dots and noise dilution. The signal dot density was held constant across all trials, therefore a change in the signal to noise ratio varied only the absolute numbers of signal and noise dots. The noise dilution of the symmetric stimulus was also removed. This was achieved by restricting the size of the target area in which the symmetric signal could fall. The symmetric dots occupied only a sub-patch of the stimulus window and the noise dots occupied the remaining area surrounding the target patch. The size of the patch was varied in proportion to the stimulus level in order to maintain a constant signal density within the patch and a uniform dot density across the entire display thereby eliminating dot density cues to the position of the target patch inside the stimulus window.

In this condition the absolute number of signal dots varied with SNR as in Experiments 1, 2, & 3. However the variable patch size had the effect of stabilising the signal dot density across all stimulus levels. This had a corresponding effect on the other stimulus factors.

Firstly, the size of the target patch was determined by the stimulus level (i.e., the number of signal dots on any trial). Therefore the maximum possible separation between any two dots is limited to the width of the target patch. At low SNRs the signal dots were limited to a relatively small area around the axis. In the extreme case of one dot pair the maximum point pair separation was 10 pixels.

With increasing SNR, the patch size is increased, thus increasing the maximum point pair separation in absolute terms. However because the number of signal dots increases with patch size the mean distance between dots remains constant in proportion to the number of dots with the consequence that matches close to the axis of symmetry were equally probable across all stimulus levels.

Moreover the statistical spatial relations between dot pairs remained constant across all stimulus levels with the consequence that feature clusters were more likely to emerge than in Experiments 1, 2 & 3.

Finally under this condition the noise was excluded from the symmetric target region and confined to the surrounding area. This removed the disruption of local matches by noise dots.

5.2 Experiment 4 - Symmetry detection under conditions of constant signal density.

5.2.1 Introduction

This experiment investigated the detectability of symmetric targets of constant density and no noise dilution under conditions of known and unknown axis position.

5.2.2 Method

Stimuli

Patterns on a 200 by 200 pixel field were generated using a random number generator to select dot positions. The composition of the stimuli was such that the symmetric dot pairs were laid within a constrained square patch inside the stimulus window thus forming a target patch within the stimulus window.

The area of the target patch was proportional to the number of signal dots on each trial. It varied between 200 by 200 pixels (at an SNR of 1 the target patch covered the full area of the stimulus window) and 0 by 0 pixels (where no symmetry was present).

The variable target area ensured that the dot density was uniform across the stimulus window at all cue sizes. Noise dots were laid at random positions in the window area surrounding the target patch. There was no detectable boundary edge between the target and the noise. Sample stimuli are shown in Figure 5.1.

In the first condition the position of the target patch was centrally positioned in the stimulus window. In the second condition the position of the target patch within the stimulus window was varied between trials. The only constraint on the axis position was that it should allow the entire target to fall inside the stimulus window. For each trial the axis position was randomly selected from the range of values which satisfied this criterion. This range of values becomes increasingly restricted at higher SNRs because the target patches are larger therefore the axes are necessarily closer to the centre of the image. However the random presentation of stimulus levels reduces as far as possible the reliability of this cue to axis position on any single trial. In all trials the axis of symmetry was vertically positioned through the midline of the target patch.

Subjects

The subjects in this experiment were TMC, CBH, and HEB (see General Methods for subjects' details).

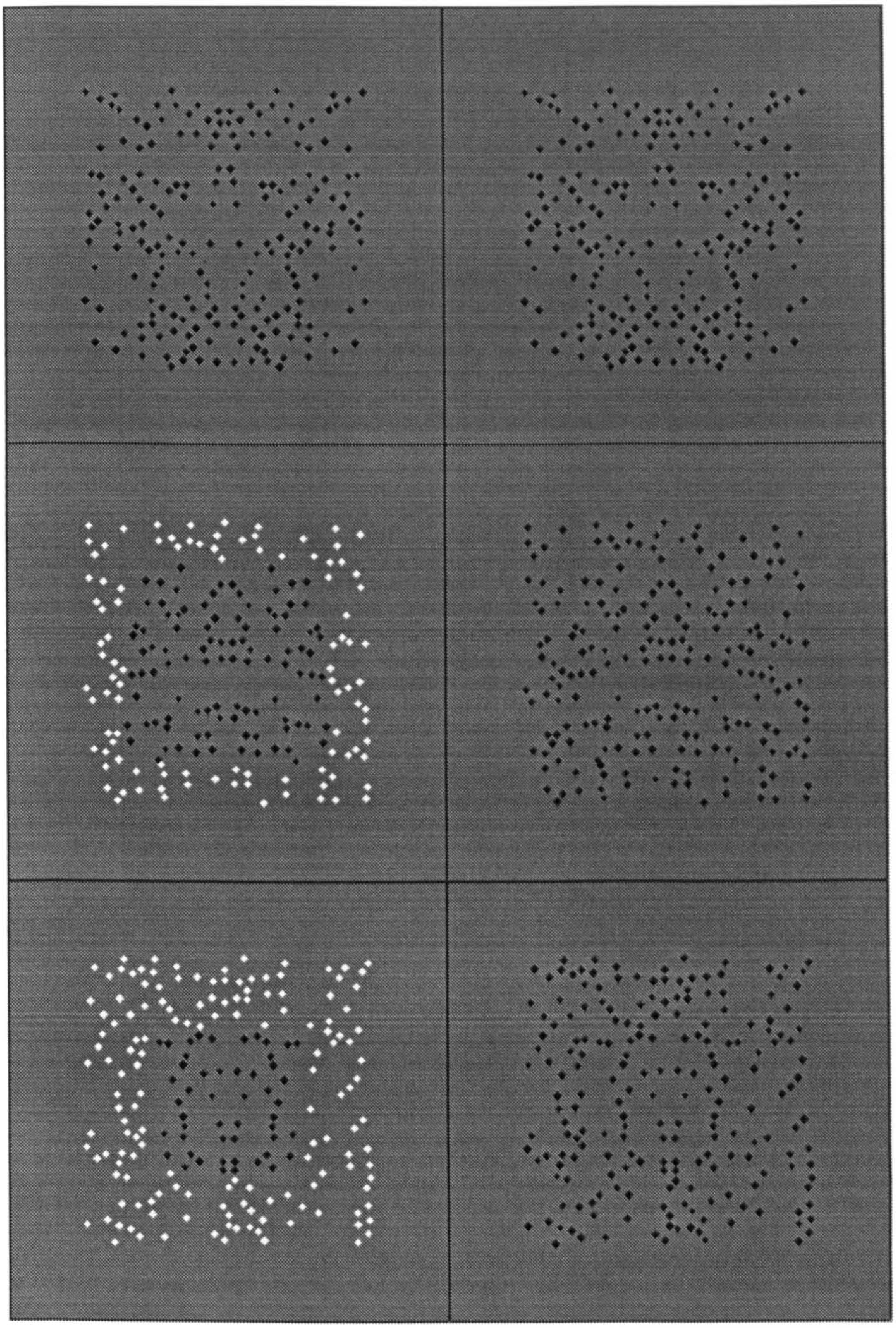


Figure 5.1. An example of the random dot symmetry pattern used in Experiment 4. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the noise dots are shown in white and the symmetric dots in black. In the right hand column, the stimuli are as presented to the subjects. It can be seen that as SNR is decreased, the size of the target is reduced and the signal density remains constant, as does the likelihood of close matches. In the random axis condition the position of the target was varied within the stimulus window.

Task

The subject's task was to indicate which of the two stimuli presented on each trial contained the symmetric stimulus. Subjects were shown a number of sample stimuli to explain the task, which made clear the position and orientation of the axis as well as the range of target sizes.

5.2.3 Results

The data from this experiment are summarised in Figure 5.2, which shows the detection threshold obtained from each subject. In the fixed axis condition, thresholds obtained are between 1% and 7% signal for all subjects. For this task, the subjects require less than 7 dot pairs out of a potential 100 pairs to detect symmetry at threshold. In the variable axis condition the thresholds are higher, ranging between 17% and 29% signal

Figure 5.2 shows the psychometric functions obtained from the three subjects in this experiment. The psychometric functions obtained show that in the fixed axis condition perfect discrimination is achieved at full signal and is sustained across virtually the full stimulus range, beginning to deteriorate only at very low signal. In the variable axis condition perfect discrimination is achieved at full signal, only beginning to deteriorate at around 30% signal. Chance performance is reached below 10% signal.

The psychometric functions from the two conditions were compared and performance was found to be significantly poorer in the variable axis condition (CBH, $p < 3*10^{-9}$; HEB, $p < 9*10^{-8}$; TMC, $p < 9*10^{-11}$).

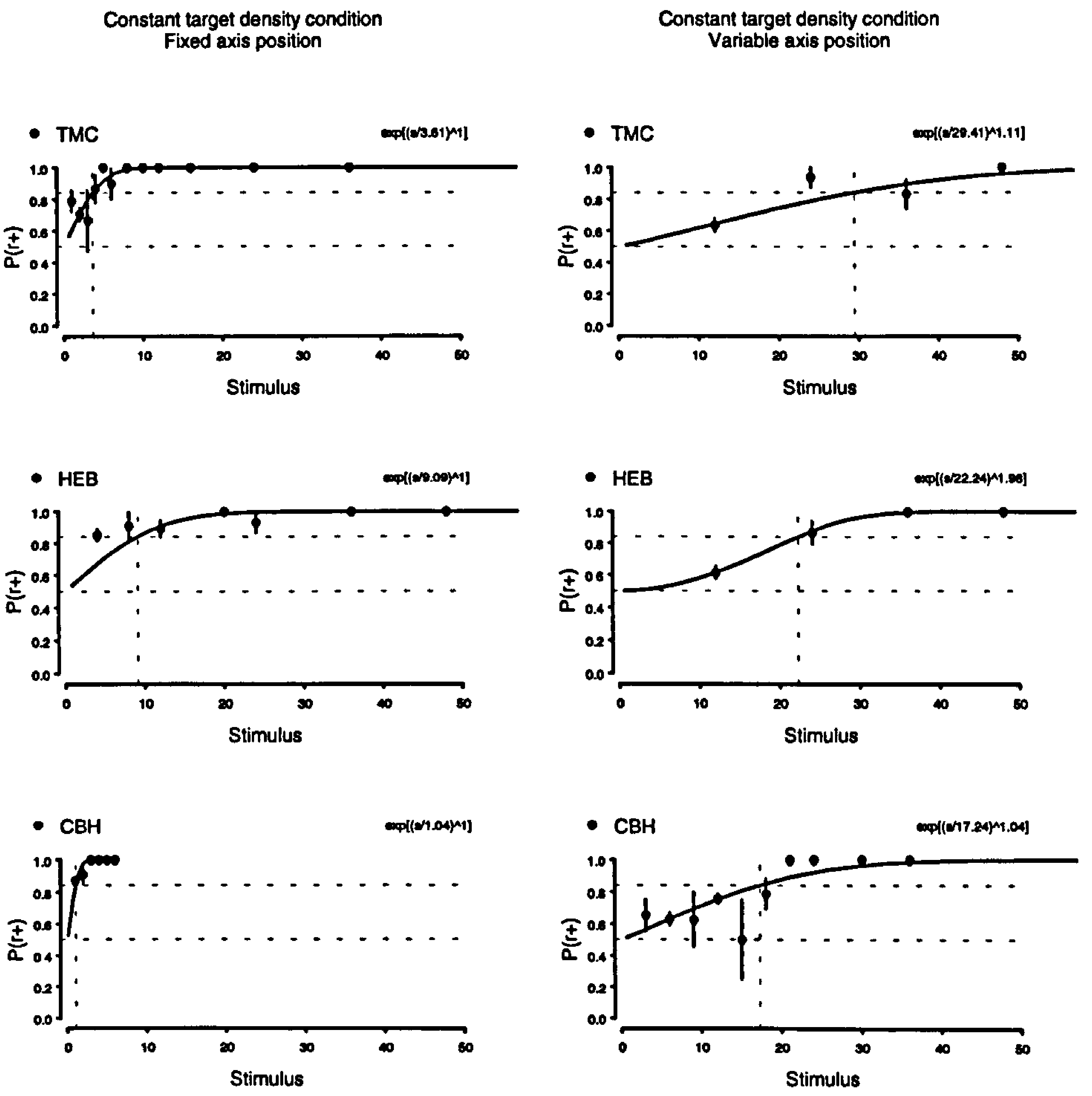


Figure 5.2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

5.2.4 Discussion

The detection thresholds in this experiment are considerably lower than in Experiments 1-3. Perfect performance is preserved across gross changes in the absolute number of signal dots, under conditions which hold other stimulus factors constant. The data from the random axis condition reveals that varying the axis position between trials causes a marked decrease in detection performance. Subjects require more symmetric dot pairs to detect symmetry when they have no prior knowledge of the axis position.

The fact that the symmetric targets can be reliably detected in the fixed axis condition given only a few, or even just one dot pair, very strongly suggests that the absolute number of dot pairs present is not a strong determinant of performance on this task, nor is the overall density of the signal dot pairs.

The results of Experiment 4 suggest that in the fixed axis condition subjects are detecting the presence of closely matched dots. One explanation for the massive improvement in detection performance in comparison with Experiments 1 and 2 is that the probability of close matches occurring is stable across all stimulus levels. In Experiments 1 and 2 however, this probability decreased as the signal to noise ratio was decreased making a purely local strategy unreliable across the stimulus range. Moreover, at the lower stimulus levels the spread of these pairs along the length of the axis is increasingly restricted by the height of the target patch, the consequence of which is to localise the target dots in the centre of the display. A highly local strategy is therefore very reliable when signal density is constant, as regardless of the spatial extent of the symmetric pattern, the distribution of dots around the axis region is not affected by a change in signal to noise ratio. The symmetric pairs more distant from the axis are apparently not necessary for symmetry detection in this condition.

It has been shown that information close to the axis is sufficient to support symmetry detection in the stimuli used in Experiment 4, however there are two possible explanations for the apparent importance of information close to the axis. The first is that closely paired dots are simply more salient than more widely separated dot pairs. It has been suggested that the orientational structure in the closely aligned dot pairs may be much stronger than that of more distant pairs, and more immediately perceived (Jenkins, 1983). If it is the case that the dots closest to the axis are extremely salient, then the detection of symmetry in these stimuli may be supported solely by the very close matches. In this situation, the additional dots which are present at higher signal to noise ratios would be effectively redundant as they are distributed outside this 'pop-out' axis region.

A second possible explanation for the sensitivity to the stimuli in this task is that knowledge of axis position provides a focal point on the image which might allow the task to be done by deliberate matching or alignment of dots which fall immediately about that point. The proposal here is not that dots close to the axis are simply more salient than other dots, but rather, that given knowledge of axis position they provide the minimum information that is required to do this task.

These two explanations for the data in the fixed axis condition predict very different results from a condition in which the position of the axis is not known in advance. If the first explanation is relevant, (that closely paired dots are extremely salient) then performance should not be affected by axis uncertainty, as the close relationship between the dots and the axis is not affected by a change in axis position. However, if the second explanation is relevant, (that axis position certainty aids the accurate detection of these stimuli) then subjects should show a decline in performance, as an axis specific strategy cannot be used if the axis position is unknown.

The results of the variable axis condition indicate that the dots immediately in the axis region axis are not sufficient for symmetry detection, as the very local matches alone are not detectable without prior knowledge of their position. The very high detection performance in the fixed axis condition must therefore have been determined partially by the subjects prior knowledge of the axis position. The very close matches (i.e., those obtained below 10% signal where the target window is very small) are not in themselves salient cues to symmetry, as these cannot be detected in the absence of the axis cue.

Removing the axis cue does not eliminate the possible use of a strategy based on the detection of local matches. For example, a search strategy might be employed to detect only closely aligned dot pairs, however, the data presented here do not support such a strategy. Under conditions of fixed signal density the number of possible local matches is independent of cue size, therefore performance using a search strategy would not be expected to vary systematically as a function of cue size. Performance in the variable axis condition of Experiment 4 clearly varies as a function of signal to noise ratio, indicating that subjects are using information other than local matches.

The increase in detection thresholds as a result of varying axis position in Experiment 4 suggests that in the absence of an axis cue, symmetry detection relies on a greater number of signal dots. Given that the absolute number of signal dots has been identified as a weak stimulus factor in symmetry detection, it is necessary to consider what other associated factors are altered as signal to noise ratio is increased and which of these may determine symmetry detection performance.

As the number of signal dots is increased, the area across which they are distributed is increased proportionally. In the fixed axis condition, detection was possible on the basis of very few locally distributed dot pairs, and the more widely distributed dots were found to be unnecessary for the task, however in the variable axis condition subjects are apparently making some use of these relatively distant dot matches. However they do this, it is not by point matching, which would not be possible without a given axis about which to match. In the variable axis condition, specific knowledge of axis position can only be gained by firstly detecting the symmetry. Logically, the symmetry cannot be detected using only a point matching strategy.

Detection performance in the variable axis condition cannot be based on accurate knowledge of axis position, however the stimuli may support a global detection strategy at the higher signal to noise ratios. The reason for this is that although the signal dots are distributed randomly on either side of the axis, a random distribution does not necessarily yield a uniform spread of dots. The signal dots fall into patterns of clusters, strings etc., and where these occur they form larger features which are themselves symmetrically arranged. These features are not carried solely in the outline shape information as subjects can achieve perfect performance with at least 50% noise in the stimuli which is distributed around the edges of the symmetric pattern, thereby disrupting outline shape. Tolerance to this noise suggests that the global features emerge not only as pattern contours but as large scale features within the symmetric outlines.

The increase in detection thresholds due to the variable axis indicates that the presence of local axis matches are not sufficient for symmetry detection, and that subjects require these larger emergent symmetric features for detection under unknown axis conditions.

The different levels of performance in the fixed and variable axis conditions is suggestive of two separate strategies in symmetry detection. A local strategy exists which is dependent on prior knowledge of the axis position, and which can detect symmetry given only a few dot pairs positioned in the axis region. Under positional uncertainty a global detection strategy can be used which does not detect individual pairwise matches but which relies on detection of the larger shapes which emerge from the multi-local relations between matched pairs.

The effectiveness of both of these strategies appears to be dependent on the density of the signal dots in the stimulus, for the reasons that high density stimuli contain a high number of close axis matches and closely related matched pairs.

One further possible reason for the high levels of detection performance in comparison with that obtained in Experiments 1-3 is that in these stimuli the noise is distributed only around the edges of the symmetric target. In the first three experiments the targets were both embedded in, and diluted by, distributions of random noise dots. Experiment 5 investigates the effect of adding noise dilution to the target patch on performance under both fixed and variable axis conditions.

5.3 Experiment 5 - The effect of noise dilution on symmetry detection under conditions of constant signal density.

5.3.1 Introduction

Experiment 4 established that of the stimulus factors which co-vary with signal to noise ratio, signal dot density and proximity to the axis are more powerful determinants of performance than the absolute number of signal dots. The contribution of these two factors is further dependent on whether the axis position is known to the subject. Signal density is particularly important in global detection of targets whose position is unknown to the observers, whilst proximity to the axis is a strong determinant of local information about a known axis position.

In order to dissociate the effects of signal density and noise dilution, the previous experiment was repeated except that additional noise dots were added to both the symmetric target region of the stimulus and the noise surround. The consequence of this is that total dot density is reduced as the signal to noise ratio is reduced.

5.3.2 Method

Stimuli

The stimuli were similar to those in the previous experiment, comprising a target patch which varied in size relative to the signal to noise ratio and a noise surround. However in this experiment, the proportion of noise dots was distributed across the entire stimulus display, rather than being restricted to the surround area. The result of this was a reduction in the density of the dots in the surround area and an increase in the density of the target patch therefore it was necessary to add further noise dots to the surround area in order to avoid any density cues to target position. Although the signal dot density was held constant as in the previous condition, the total dot density in the target patch now increased as stimulus level decreased, therefore the number of additional noise dots required to balance density over the display was increased proportionally. The total number of dots in the display therefore increased as the signal to noise ratio decreased. Sample stimuli are given in Figure 5.3.

This condition was run under both fixed and variable axis positions. In the fixed position condition the target patch was central in the stimulus window and the axis of symmetry was vertically positioned through the midline of the target patch. In the variable condition the position of the target patch within the stimulus window was varied between trials. The only constraint on the axis position was that it should allow the entire target to fall inside the stimulus window. For each trial the axis position was randomly selected from the range of values which satisfied this criterion. This range of values becomes increasingly restricted at higher SNRs because the target patches are larger therefore the axes are necessarily closer to the centre of the image. However, the random presentation of stimulus levels reduces as far as possible the reliability of this cue to axis position on any single trial.

Subjects

The subjects in this experiment were TMC, LJM, and MB (see General Methods for subjects' details).

Task

The subject's task was to indicate which of the two stimuli presented on each trial contained the symmetric stimulus. Subjects were shown a number of sample stimuli to explain the task, which made clear the orientation of the axis as well as the range of target positions and sizes.

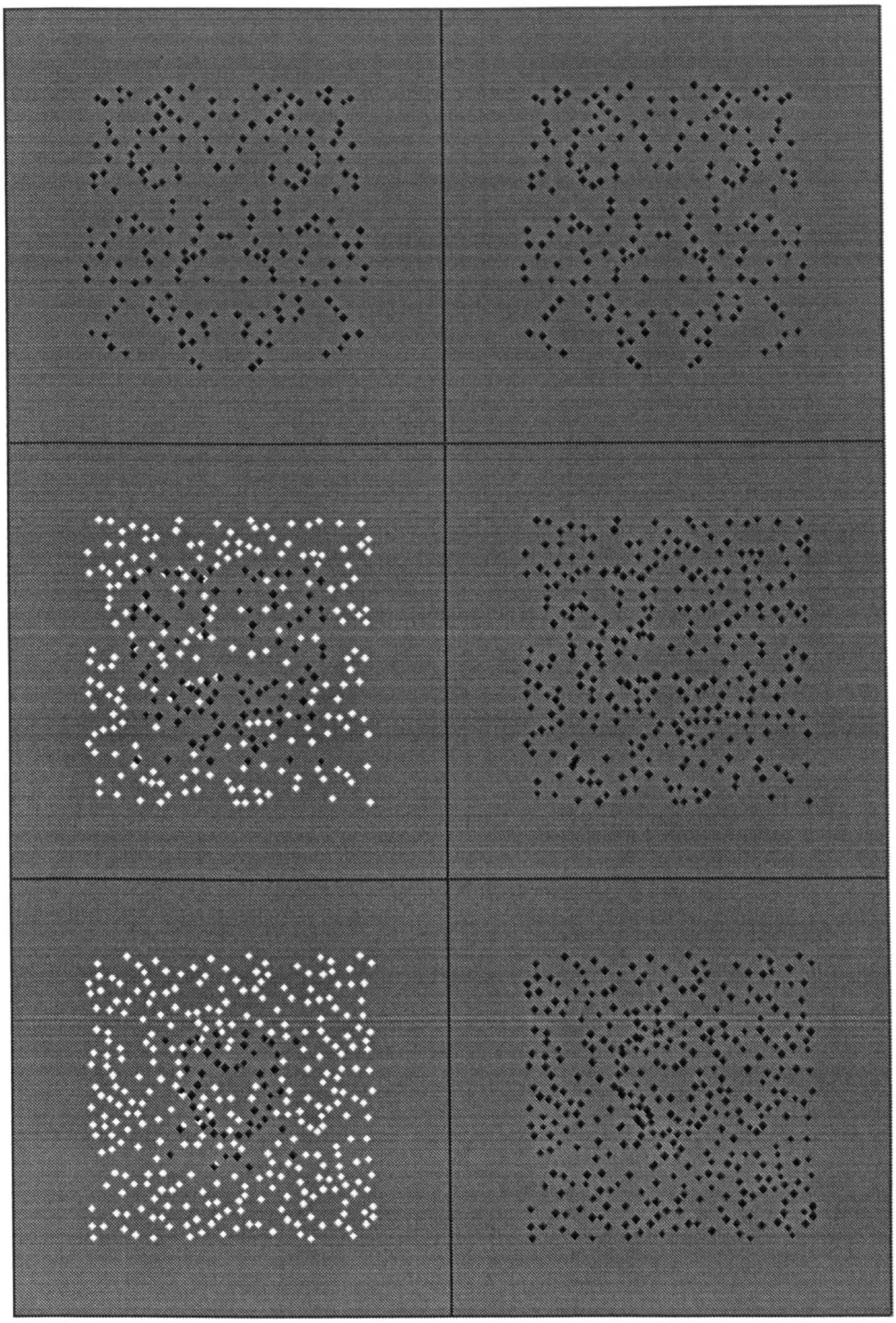


Figure 5.3. An example of the random dot symmetry pattern used in Experiment 5. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the noise dots are shown in white and the symmetric dots in black. In the right hand column, the stimuli are as presented to the subjects. It can be seen that as SNR is decreased, the size of the target is reduced and the signal density remains constant, as does the likelihood of close matches. Because the signal density is constant, the overall density of the target patch increases as SNR increases. To compensate for this, additional noise dots are added to the surround and the result of this is that the total number of dots in the stimulus increases as SNR increases. In the random axis condition the position of the target was varied within the stimulus window.

5.3.3 Results

The data from this experiment are summarised in Figure 5.4 which shows the psychometric functions obtained from each subject in both fixed and variable axis positions. In the fixed axis condition the thresholds range between 23% and 27% signal across subject. In the unknown axis condition, the detection thresholds were higher, ranging between 53% and 62% signal.

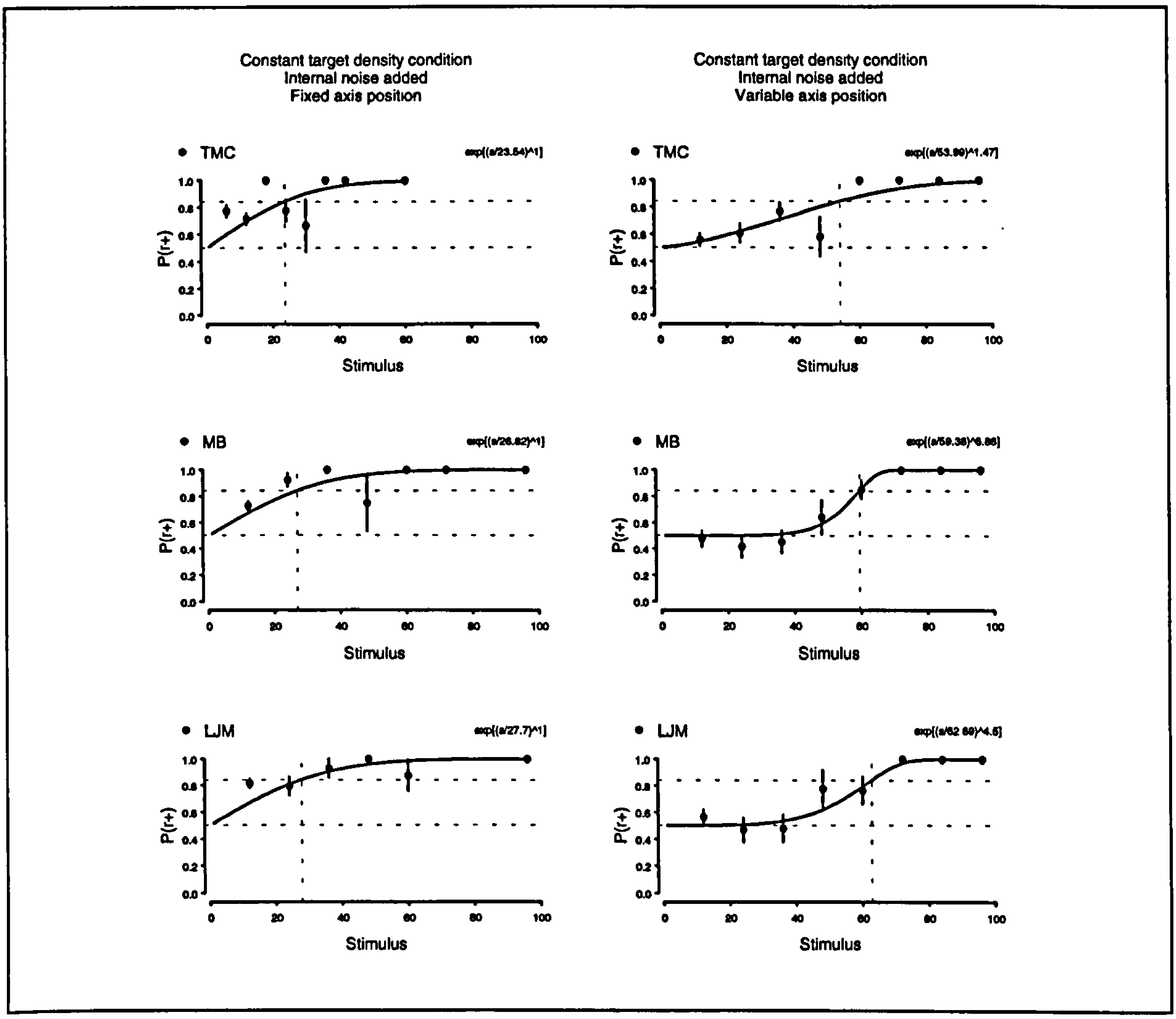


Figure 5.4. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

The psychometric functions from the fixed and variable conditions were compared and performance was found to be significantly poorer in the variable axis condition (LJM, $p < 4*10^{-9}$; MB, $p < 5*10^{-9}$; TMC, $p < 5*10^{-5}$). The psychometric functions were not different across the whole range, as subjects achieved perfect or near perfect detection performance at the higher stimulus levels (60-100% signal) in both fixed and variable axis conditions. However, the functions were found to diverge at the middle to low stimulus levels (12-36% stimulus), due to a more rapid deterioration in performance in the variable axis condition. This indicates that a relatively sudden perceptual change occurs in the middle range, and that detection in the fixed axis condition is sustained across a wider range than in the variable condition by the use of local axis cues.

The thresholds obtained in this experiment are considerably greater than those in Experiment 4. In the central axis condition, the mean number (for the three subjects) of signal dot pairs required for threshold detection increased approximately fourfold as a result of the additional noise dilution (from 4 pairs to 24 pairs). In the variable axis condition, the mean number of dots required was around 2 ½ times higher (increasing from 22 pairs to 58 pairs at threshold). Only one subject (TMC) was common to the two experiments and detection performance was found to be significantly poorer in this experiment, under both fixed and variable axis conditions (TMC, fixed axis, $p < 0.015$; variable axis, $p < 0.007$).

5.3.4 Discussion

The detection thresholds in both the central and random axis conditions are increased as a result of noise dilution within the target region. There is a greater proportional increase in the central axis condition, suggesting that the local detection strategy is disrupted more than the global strategy by the noise dilution. The interaction between noise dilution and axis condition can be seen in the psychometric functions. Although the thresholds in the central axis condition are greatly increased in comparison to those in Experiment 4, detection performance is nonetheless maintained at a high level across the stimulus range and does not fall to chance level until below 10% signal. Detection is therefore only seriously impaired as the absolute number of signal dot pairs is reduced from 10 to 0. This suggests that in the fixed axis condition, subjects are able to detect some local cues to symmetry, despite an increase in noise dilution, and that whilst the presence of spurious dots in the axis region impairs the certainty of the matches, this can be compensated by the confirmatory presence of other local symmetric pairs.

In the variable axis condition, perfect performance is achieved at the higher stimulus levels, but below this point falls rapidly to chance level at around 30%-40% signal. The addition of noise does not therefore disrupt detection uniformly across the stimulus range as in the central axis condition. In this condition the relative proportions of signal and noise are crucial to detection performance. This suggests that the global detection of the symmetric targets in the presence of noise dilution is heavily dependent on stimulus factors which vary with signal to noise ratio. In these stimuli the density of the signal dots is held constant, therefore the probability of local clusters emerging is also constant across the stimulus range. However, the possible size of the emergent clusters must decrease as the number of symmetric pairs is reduced. At the higher stimulus levels, the emergent clusters are sufficiently large that they remain distinctive and salient despite minor levels of noise disruption. However as the signal level is decreased, the emergent features are reduced in size and distinctiveness and the level of background noise is increased concurrently, making the overall distribution of dots much more uniform within the target patch and merging the increasingly smaller clusters into the noise background. The combined effect of two factors may therefore explain the sharp change in the discrimination function in the variable axis condition.

The results of these experiments support the use of different detection strategies under fixed and variable axis conditions. Given that two different detection strategies appear to be used under fixed and variable axis conditions it is possible that the noise dilution affects the global and local cues to symmetry in different ways. The additional noise may disrupt the local distribution of dots about the axis by providing spurious matches for the signal dots close to the axis. The global features are more likely to be disrupted by noise dots merging with signal dot clusters producing a more uniform distribution of dots and also changing the distinctive emergent features.

The existence of two distinct strategies under these conditions and the mechanisms which may be involved in each are further investigated in Experiment 6.

5.4 Experiment 6 - The effect of mixed contrast dot pairs on symmetry detection.

5.4.1 Introduction

The results of Experiments 4 and 5 suggest that knowledge of the axis position allows a detection strategy which bypasses a global analysis of the stimuli. Using this strategy subjects can detect symmetric structure with a small number of dot pairs distributed locally about the axis. In the absence of an axis cue more global features and shapes are required for detection. The purpose of this experiment was to test these conclusions by establishing whether the global and local strategies are independent and if so what stimulus factors they rely upon.

This was carried out by the use of a task in which subjects were required to detect symmetric targets made up of opposite contrast dots. The targets were embedded in a noise background of mixed contrast dots. Performance was measured on both constant and variable axis conditions and the results compared with those from Experiment 4, in order to establish whether contrast affects performance differently under known and unknown axis conditions.

5.4.2 Method

Stimuli

The opposite contrast stimuli were similar to those in Experiment 4, comprising symmetric targets embedded in a noise surround, these varying in proportion to each other. In this experiment however the symmetrically paired elements were of opposite contrast polarity.

The order of the opposite contrast elements was randomised within each pair to ensure a random allocation of bright and dark dots on either side of the axis. Polarity of the noise dots was randomly selected for each dot ensuring a mixed contrast distribution of noise. Both constant and variable axis conditions were again presented to the subjects. Sample stimuli are shown in Figure 5.5.

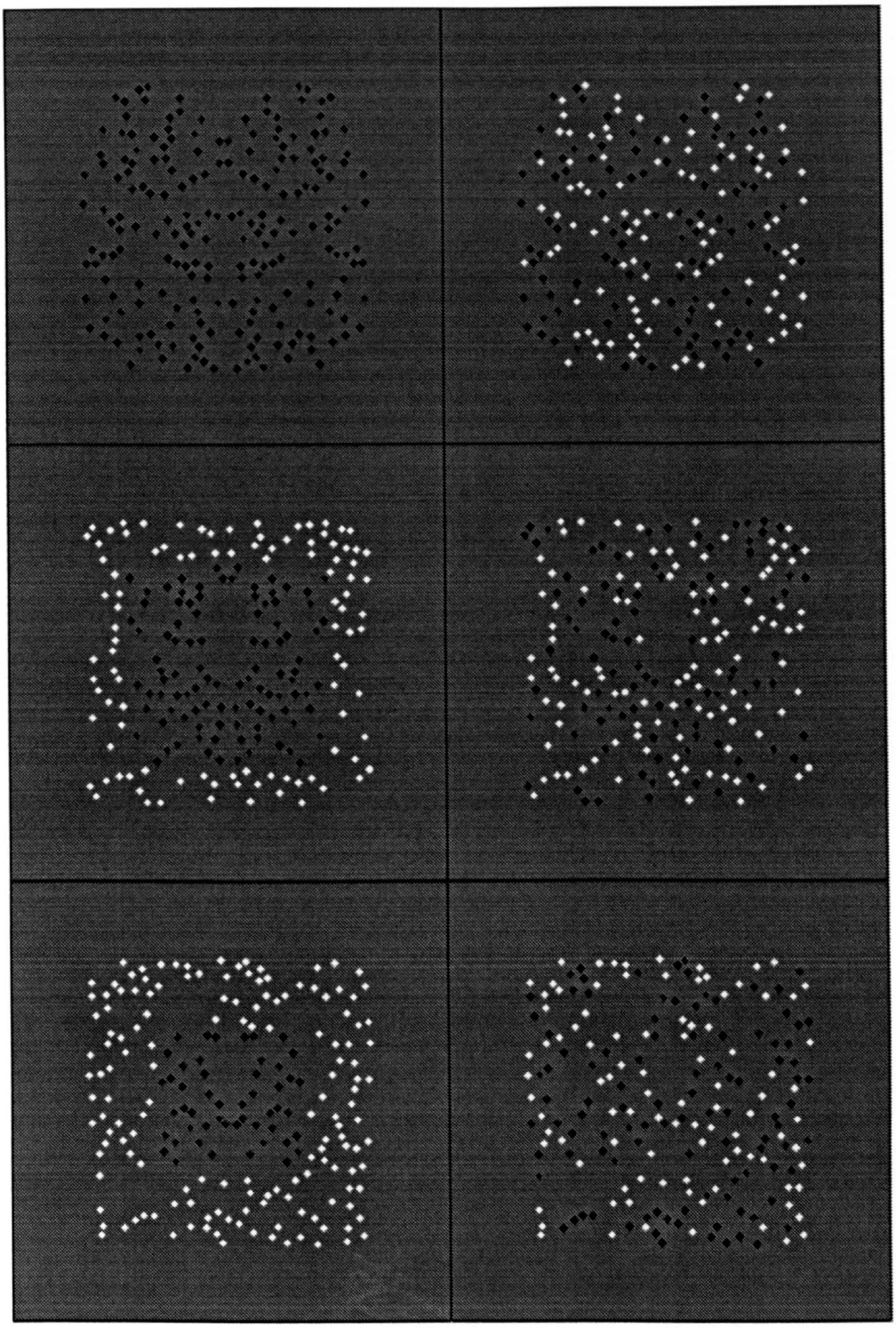


Figure 5.5. An example of the random dot symmetry pattern used in Experiment 6. In the left hand column the noise dots are shown in white and the symmetric dots in black. In the right hand column, the stimuli are mixed contrast pairs and mixed contrast noise, as presented to the subjects. In the random axis condition the position of the target was varied within the stimulus window.

Subjects

The subjects in this experiment were TMC, CBH, and HEB (see General Methods for subjects' details).

Task

The subject's task was to indicate which of the two stimuli presented on each trial contained the symmetric stimulus. Subjects were shown a number of sample stimuli to explain the task, which made clear the orientation of the axis as well as the range of target positions and sizes.

Subjects were shown a number of sample stimuli which made clear the position and orientation of the axis, the range of target sizes and the opposing contrast of the paired dots.

5.4.3 Results

Figure 5.6. shows the psychometric functions obtained from the three subjects on this task for both the known and unknown axis conditions. In the known axis condition, perfect discrimination is achieved at full signal and is sustained across virtually the full stimulus range, beginning to deteriorate below around 10% signal. In the unknown axis condition, detection performance begins to deteriorate immediately below 100% signal for two subjects and 70% signal for the third. It degrades gradually as signal to noise ratio is reduced.

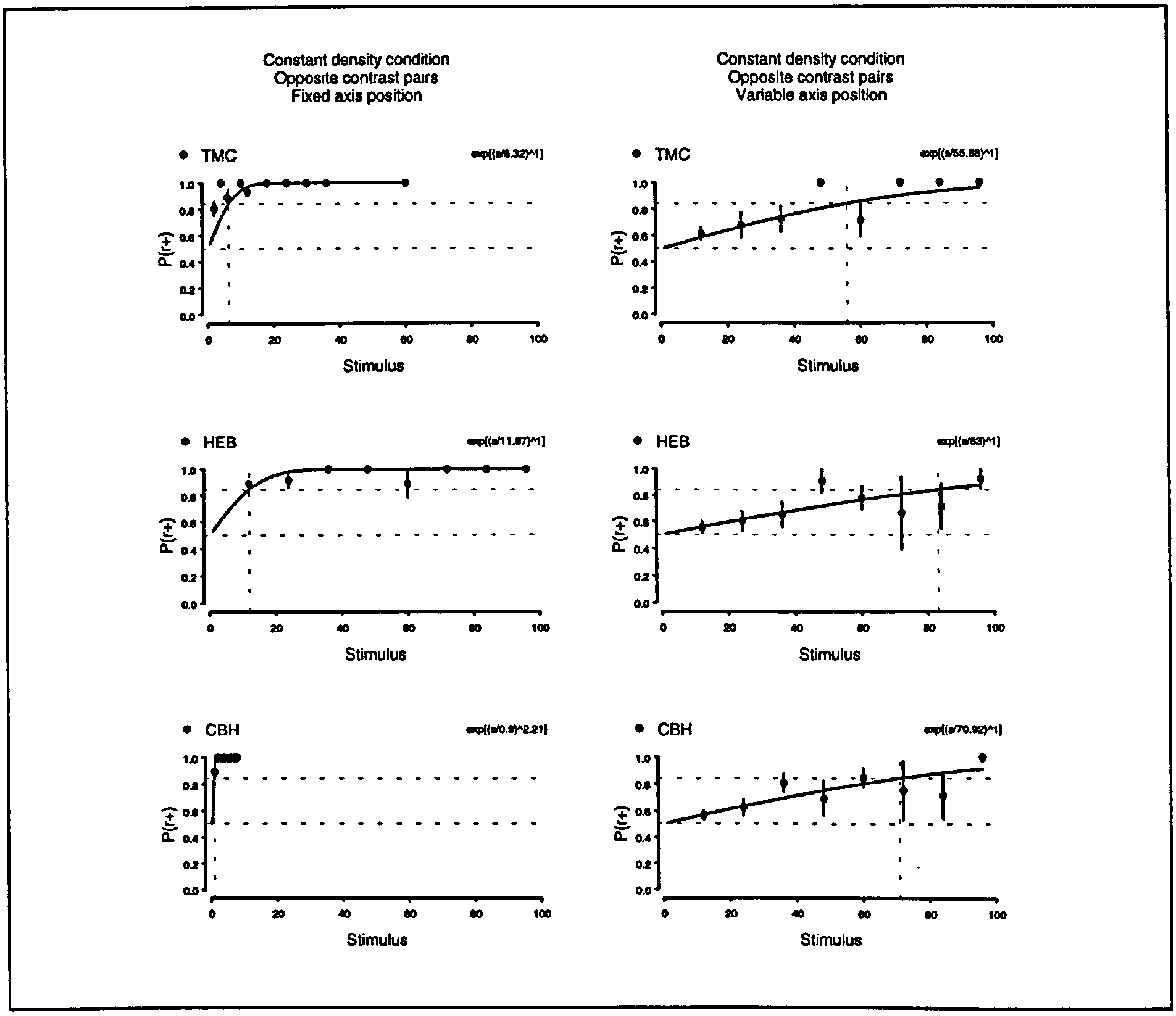


Figure 5.6. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

The data from this experiment are summarised in Figure 5.6. which shows the detection threshold obtained from each subject in both known and unknown axis positions. In the known axis condition thresholds are obtained between 1% and 11% signal. In the unknown axis condition however, the thresholds are elevated to between 55% and 80% signal.

The data obtained from the three subjects in this experiment are compared with those of Experiment 4 to show the effect of mixing luminance contrast within dot pairs. No significant differences in performance were found between detection of uniform contrast and mixed contrast pairs in the fixed axis condition. However, in the variable axis condition, performance was found to be significantly poorer for mixed contrast patterns (CBH, $p < 2*10^{-7}$; HEB, $p < 0.002$; TMC, $p < 0.006$).

5.4.4 Discussion

The results of this experiment, in comparison with those of Experiment 4 indicate that mixing the contrast of the dots has no effect on detection of fixed position targets, and a considerable effect on the detection of variably positioned targets. In the fixed axis condition, detection performance was comparable to that with uniform contrast dots. However, under the variable axis condition, performance is markedly worse with mixed contrast targets than with the uniform targets.

That the opposite contrast dots differently affect performance in the known and unknown axis conditions provides further support for the use of independent detection strategies under the two axis conditions. Symmetry detection under known axis conditions is not dependent on contrast. This suggests that axis knowledge allows a local strategy to be used which directly cues the location of closely matched pairs. As the local strategy is not affected by mixed contrast, it must rely on detection of the position and alignment of individual dots distributed locally about the axis. The unknown axis condition is contrast dependent, therefore in the absence of axis knowledge, symmetry detection relies on features emerging in clusters of dots, which are grouped by contrast.

5.5 General discussion

In drawing together the results of experiments in Chapters 4 and 5 it is possible to draw some conclusions about the major determinants of symmetry detection in random dot patterns.

Firstly, as found by Barlow and Reeves, it was shown in Experiments 1, 2, and 3 that symmetry detection is not a discrete, all or nothing process, but that detection ability degrades as the proportion of signal to noise is reduced in the stimulus. This fact alone provides little information about the cues to symmetry in the random dot stimuli used in these experiments, particularly as a change in the signal to noise ratio does not have a unitary effect on the stimulus, but concurrently alters a number of stimulus factors.

A decrease in the signal to noise ratio reduces the absolute number of signal dots. As this happens the signal dot density is also reduced with the result that the symmetric pairs are more sparsely distributed across the stimulus. Moreover, the probability of close matches occurring in the axis region is also decreased, and, the amount of noise dilution in the stimulus is increased in proportion to the reduction in signal.

In Experiments 4 - 6 the effects of the above factors were tested individually, and the results obtained indicate that they contribute in very different ways to perception of symmetry. More importantly, strong interactions with axis condition were observed.

The absolute number of signal dots present was found to be a weak determinant of detection ability. In Experiments 1 and 2, despite the presence of an axis cue, threshold detection required 50-80% signal dots. In contrast to this result it was established in Experiment 4 (central axis condition), that given both an axis position cue and a local distribution of signal dots about the axis region, subjects were able to detect as few as 1-7 symmetric dot pairs. Clearly the presence of close point pair matches are an important stimulus factor under known axis conditions, regardless of the absolute number of dot pairs present.

The contribution of signal dot density to symmetry detection was highlighted in the difference in results between Experiments 3 and 4 (variable axis condition). In Experiment 3, the density of the signal dots was variable across the stimulus range and threshold detection required 68-88% dot pairs, which compares poorly with the 17-29% signal required under the conditions of constant signal density in Experiment 4. Again, this result indicates that the absolute number of signal dots is a relatively weak determinant of performance and that of greater importance is the signal dot density and the resultant grouping factors which emerge in conditions of high signal density. Under conditions of axis positional uncertainty, the grouping of local dot clusters into larger features was found to be prerequisite to the detection of global symmetry in random dot patterns, and the results of Experiments 5 and 6 revealed that at least two of the essential conditions for grouping were the presence of nonuniformly distributed elements, and contrast uniformity within the local clusters.

Perhaps the most pertinent finding of this series of experiments is that in random dot stimuli, a highly specific detection strategy is consistently used by subjects, under all conditions in which the position of the symmetry axis is fixed in the display. A fixed axis position provides an implicit axis cue to the subjects, and given this cue, they are able to adequately perform on a discrimination task, apparently with no reference whatsoever to the global structure in the pattern. The extent to which any results obtained under such conditions can be interpreted in terms of the global attributes of symmetric structure is questionable. For the purposes of this thesis which is concerned with the role of global or Gestalt properties of symmetric structure in preattentive image segmentation, it is essential to ensure as far as possible that subjects are not using this kind of local detection strategy to solve discrimination tasks.

For the remainder of the experimental research in this thesis, the main interest is in observing the global perceptual attributes of symmetric structure. The standard random dot pattern may not be the best type of stimulus for this purpose, as the perception of global symmetry in random dot patterns has been found to be fragile, except under the optimal conditions of high density, no noise dilution and uniform contrast. In order to meet these conditions the stimuli must be highly constrained. For these reasons a novel type of random stimulus is introduced in the following experiments, which is designed such that the optimal conditions for detection are met without tightly constraining the stimulus layout. Moreover, in these stimuli, local information is of limited use to the subjects therefore symmetry detection is forced towards more global cues.

6

SYMMETRY DETECTION IN DISC PATTERNS

6.1 Overview

In the experiments of Chapters 4 and 5 it was established that given no prior knowledge of axis position, symmetry was best detected in random dot patterns in which the signal pattern was relatively dense, of uniform contrast and undiluted by noise.

In the set of experiments to be reported in this chapter, the stimulus factors of density and contrast were incorporated into a novel set of stimuli. This was achieved by making the pattern elements large circular discs of variable size and grey level. The discs were variable between, but not within matched pairs. The elements themselves were varied in size to emulate the variably sized dot clusters of uniform contrast which were found to emerge in the dot stimuli. These stimuli were presented against a cluttered background of similar elements of variable size and intensity. These larger pattern elements therefore replaced the dense emergent clusters of the dot patterns. Like the emergent features, they had a characteristic size and a uniform intensity. In addition, the grey level provided an additional matched characteristic for each pair.

Arguably, these new stimuli contain more of the visual properties of natural images than do the standard random dot patterns used previously. The symmetries which occur in our visual environment are rarely comprised of discrete points in space, presented against a uniform background, as are the random dot stimuli. Moreover, the elements in natural symmetries are not necessarily identical across the pattern. The global symmetry in an object often emerges from the symmetric positioning of different object features which may vary in size, shape or colour. Faces are a good example of natural symmetry in which the features, or elements, vary in shape and colour along the length of the axis. This sort of variability was therefore incorporated into the stimuli which were presented against a cluttered background in order to simulate the visual task of extracting an object from a noisy nonuniform background.

6.2 Experiment 7 - Symmetry detection in disc patterns

6.2.1 Introduction

The purpose of this experiment was to measure symmetry detection performance under known and unknown axis conditions using the disc stimuli of variable size and grey level. Given these stimulus conditions, thought to be optimal for global symmetry detection, it was predicted that smaller performance differences would be found between the fixed and variable axis conditions than were found in the previous experiments with dot pattern stimuli.

6.2.2 Method

Stimuli

The displays in this experiment comprised stimulus windows embedded in a noise background. The stimulus windows contained symmetric blob pairs (targets) and uncorrelated blobs (noise) in varying signal to noise ratios (SNRs). The noise background contained only uncorrelated blobs.

The blobs varied in size and grey level with values randomly selected from a size range of 6-20 (0.06 deg-0.18 deg at a viewing distance of 4 metres) pixels and a grey level range of ±120 grey levels.

The background window measured 300 by 300 pixels. It contained 300 randomly distributed discs covering all of the background window.

The stimulus windows measured 200 by 200 pixels and were placed on top of the noise background.

Because overlap between blobs was permitted in this condition the symmetric targets were laid down last in order that the target elements would not be occluded by noise. It was important that the targets were always fully visible and not randomly occluded by noise elements as this would produce irregularities across the range of signal to noise ratios.

The axis of symmetry was either positioned centrally in the stimulus window or varied within the background window between trials. The only constraint on the axis position was that it should allow the entire target to fall inside the stimulus window. For each trial the axis position was randomly selected from the range of values which satisfied this criterion.

Changes in the proportion of signal to noise elements occurred only within the embedded target window. The background elements were in addition to this and remained constant in number. Sample stimuli are given in Figure 6.1. Note that in these stimuli, 100% signal indicates that all of the target discs are paired, that is, the target is comprised of 50 disc pairs. However, due to the fact that these targets are placed upon a noise background, uncorrelated discs are present in the larger window surrounding the target and also in the spaces between the target discs. Thus, even at 100% signal (top row of Figure 6.1) the target stimuli are not noise free.

Subjects

The subjects in this experiment were TMC, CBH, and LAW (see General Methods for subjects' details).

Task

The subject's task was to discriminate the target stimulus containing the symmetrically placed elements from the distractor stimulus containing only uncorrelated elements. Subjects were shown a number of sample stimuli to explain the task, which made clear the range of positions and orientation of the target stimuli within the background window.

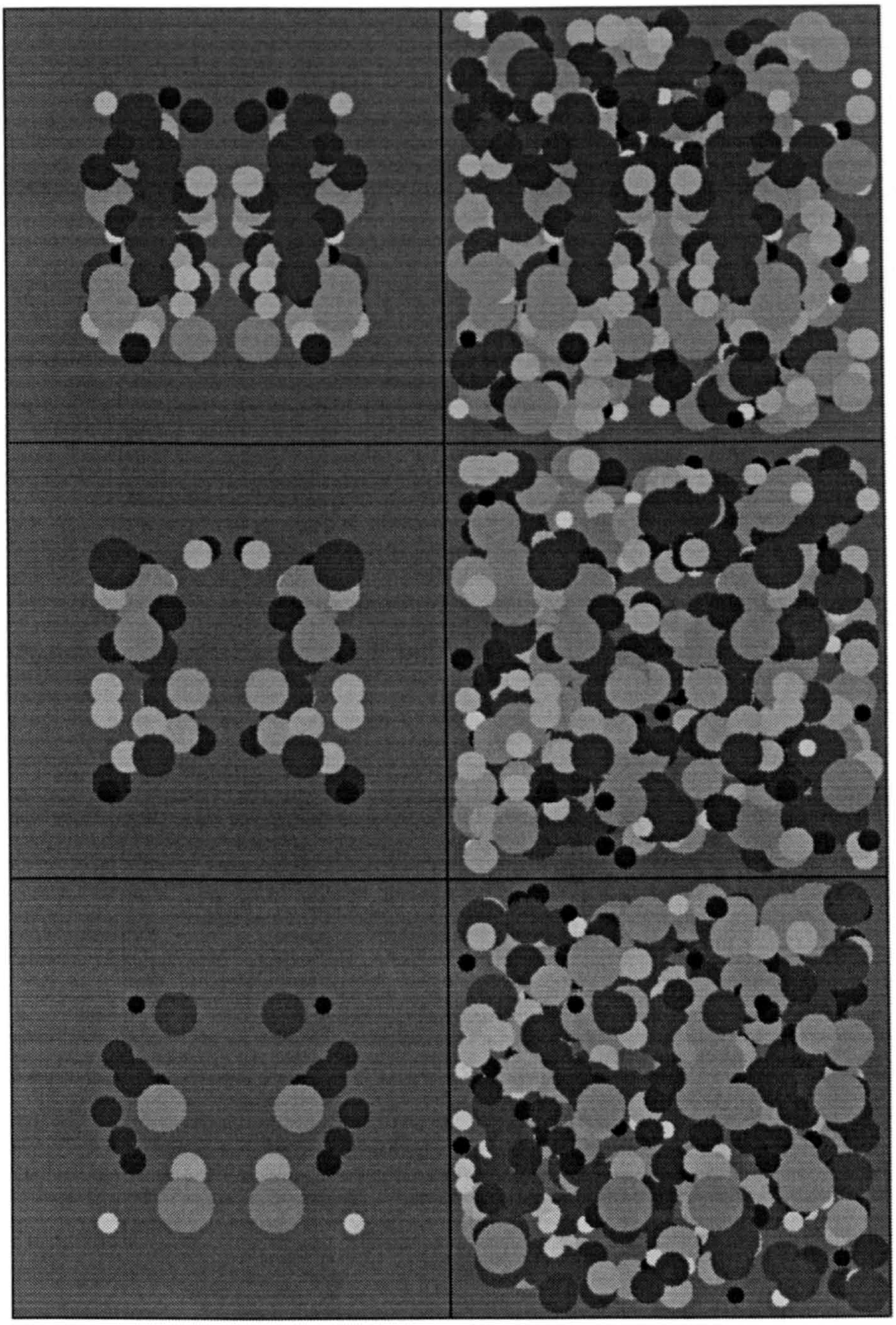


Figure 6.1. An example of the random disc symmetry pattern used in Experiment 7. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that disc size and grey level are matched within pairs, but vary between pairs. The signal dots frequently occlude one another. In the random axis condition the position of the stimulus window was varied within the outer background window.

6.2.3 Results

Figure 6.2 shows the psychometric functions obtained from the three subjects on this task, for both the fixed and variable axis conditions. In both conditions, perfect discrimination is achieved at full signal, and a high level of detection performance is sustained across a wide stimulus range, beginning to deteriorate at around 60-80% signal in the unknown axis condition and 40-60% signal where the axis was known.

The psychometric functions from the two conditions were compared and no significant effect of axis knowledge was found. Although performance is slightly and systematically worse in the variable axis condition, the discrimination functions for the two conditions are very similar in shape. This suggests that there is no qualitative perceptual difference in the stimulus under these two conditions.

The data from this experiment are summarised in Figure 6.2, which shows the detection thresholds obtained from each subject in both known and unknown axis positions. The thresholds were calculated from only the 100 elements in the smaller stimulus window, discounting the 300 background elements. In the fixed axis condition the thresholds range between 28% and 36% signal across subject, meaning that for this task, the subjects require at least 14 to 18 disc pairs out of a potential 50 pairs to detect symmetry at the 83% detection threshold. In the variable axis condition the thresholds are slightly elevated to between 38% and 48% signal (19-24 pairs).

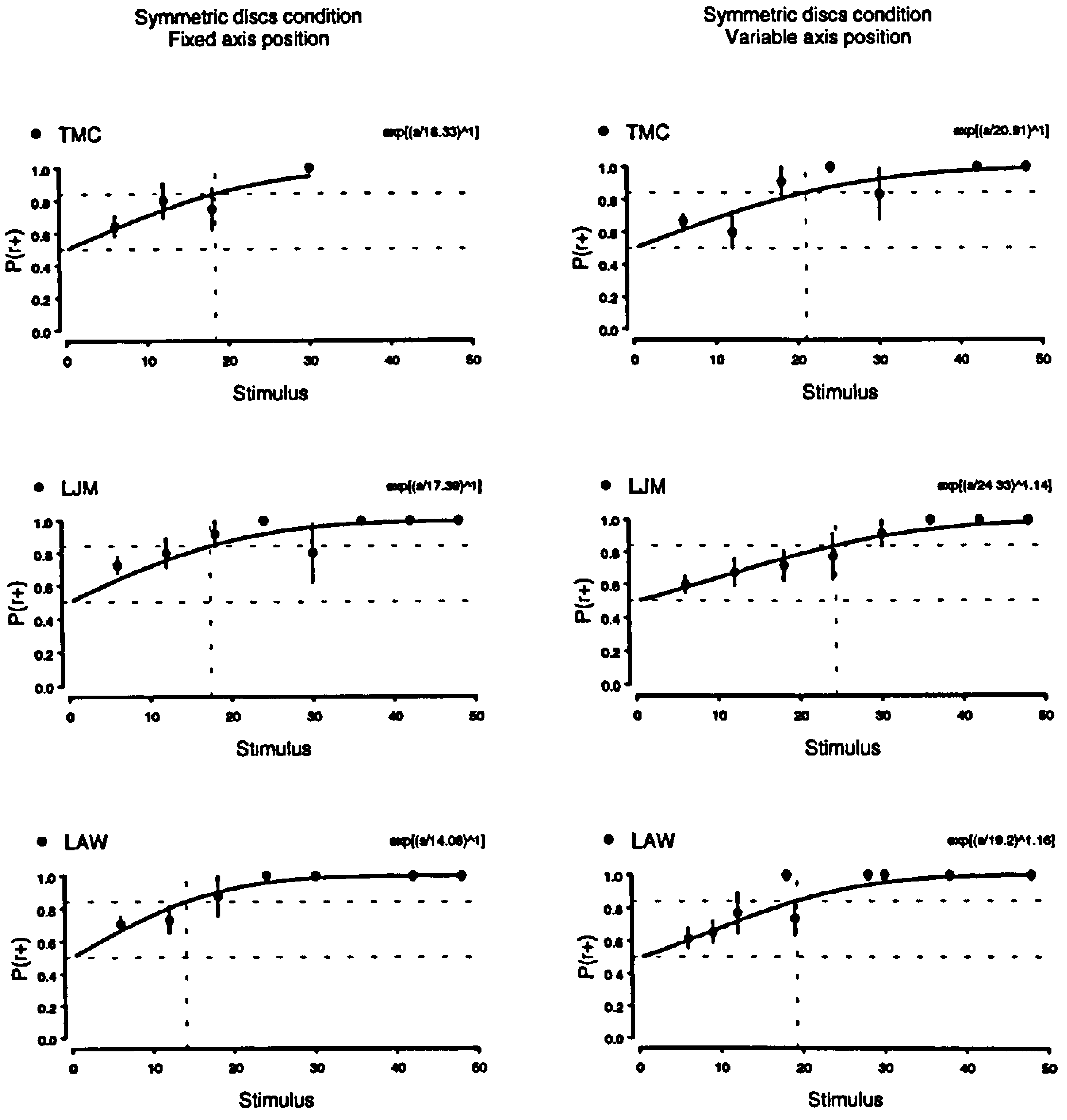


Figure 6.2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

6.2.4 Discussion

Because performance measures are translated into the number of symmetric pairs required at threshold, performance on this task cannot be directly compared with that on the random dot tasks, as the elements in these stimuli overlap, making it impossible to know precisely how many signal pairs were presented to the subject on a trial. The number of visible disc pairs in these displays may be less than the corresponding stimulus level due to this overlap, therefore the threshold estimates obtained in this series of experiments may be slightly overestimated in comparison with those obtained in the random dot tasks.

The effect of the new disc elements on detection performance is therefore not observed in the absolute difference in thresholds between the dot and disc stimuli, but rather in the finding that a much less pronounced effect of axis knowledge is found with the disc stimuli than was found with the dot stimuli. The psychometric functions from both the fixed and variable axis conditions are similar in shape and slope across the stimulus range. This suggests that prior knowledge of the axis position has no qualitative effect on the perception of symmetry in these patterns., and that similar cues may be used in both the known and unknown axis conditions. If this is the case, then logically, these must be global cues, as local information is not available under random axis conditions.

It is concluded then, that symmetry detection in these disc patterns can be considered to be presegmental. The slight but consistent advantage for fixed position targets suggests that there may be some residual local cues in the fixed position targets.

The fact that the removal of axis information has only a very slight effect on detection performance indicates that there is a lesser advantage for axis position knowledge in these stimuli than in the dot stimuli. A number of stimulus factors might account for this.

Firstly, the random dot stimuli were comprised of black dots on a uniform grey background, whereas in these stimuli the pattern elements were laid on a background of discs from the same intensity range. The contrast difference between the signal and the background was therefore much reduced in these stimuli, and was variable across the display. Because of this, the individual signal discs were not clearly discernible from the background at a viewing distance of 4 metres, making detection of positional alignment of individual disc pairs much more difficult than in the dot stimuli, in which the pattern elements were high contrast and presented against a uniform background. Given this difficulty in picking out individual elements, a local element matching strategy based on close inspection of disc position and alignment is made difficult in these stimuli, even with prior knowledge of axis position. The slight detection advantage for fixed position stimuli suggests that there is still some additional cue to symmetry given by this information, however, the similar patterns of performance in both the fixed and variable axis conditions suggest that symmetry is detected by a more global strategy which is relatively independent of axis knowledge.

In order to determine which stimulus features of these new stimuli carry the global symmetry information, the characteristic features of size and grey level were selectively disrupted in the following experiments, in order to determine the effect of these variables on symmetry detection.

6.3 Experiment 8 - The effect of varying disc size within pair matches

6.3.1 Introduction

The results of the previous experiment suggest that the symmetric disc targets may be detected globally and that prior knowledge of axis position confers no detection advantage. It is conjectured here that the accurate alignment of elements about the axis may not be the strongest contributing factor to the detection of symmetry in these stimuli.

The purpose of this experiment was to determine whether subjects could detect symmetry in the disc patterns when the discs were matched for luminance but not for size within symmetric pairs. Strictly speaking, these patterns are not perfectly symmetric, and it is of interest to find out whether a global 'symmetry-like' structure can be detected by virtue of the symmetric positioning of the differently sized elements.

6.3.2 Method

Stimuli

The stimuli were similar to those in Experiment 7 with the exception that the sizes of the matched discs were randomly selected from a range of 6 - 20 pixels (0.06 deg and 0.18 deg) in diameter. Sample stimuli are shown in Figure 6.3.

Subjects

The subjects in this experiment were TMC, LJM, and MB (see General Methods for subjects' details).

Task

The subject's task was to discriminate the target stimulus containing the symmetrically placed discs from the distractor stimulus containing only uncorrelated discs. Subjects were shown a number of sample stimuli to explain the task, which made clear the variation in disc sizes, the range of positions and the orientation of the target stimuli within the background window.

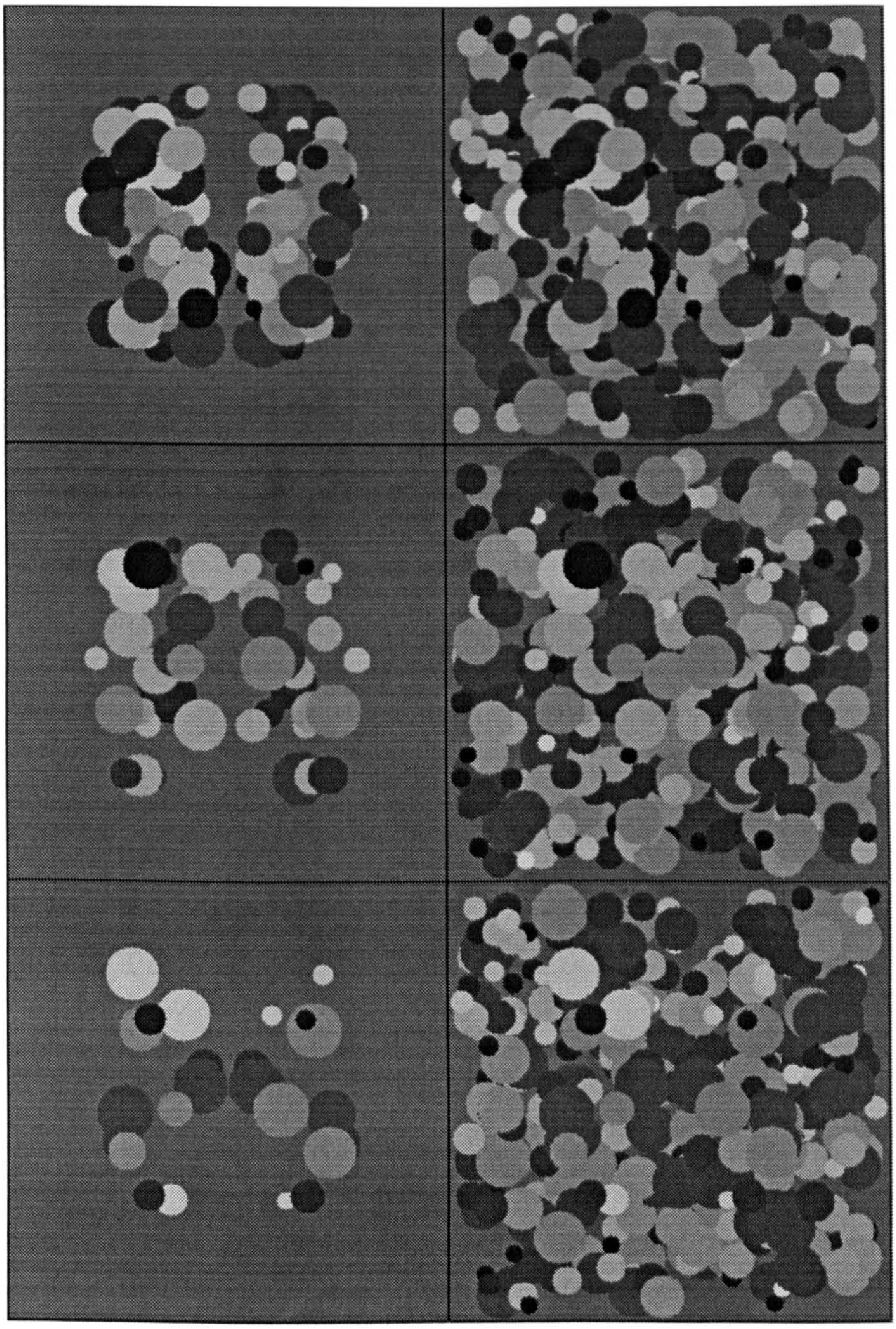


Figure 6.3. An example of the random disc symmetry pattern used in Experiment 8 (variable disc sizes). The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that disc intensity is matched within pairs, but disc size is variable both between and within matched pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

6.3.3 Results

Figure 6.4 shows the psychometric functions obtained from the three subjects on this task, for both the known and unknown axis conditions. Perfect detection performance is not always reached, even at full signal, and performance is found to deteriorate gradually, although performance across the range is slightly erratic in comparison with that in Experiment 7. It may be the case that the absolute stimulus level is not the strongest determinant of performance in this task, and that the perceived structure is varying as a function of some other stimulus factor which is not controlled here. Possible reasons for the scattered responses are suggested in the general discussion of the chapter.

The data from this experiment are summarised in Figure 6.4 which shows the detection threshold obtained from each subject in both known and unknown axis positions. The thresholds were calculated from only those elements in the smaller stimulus window, discounting the 300 background discs. In the known axis condition the thresholds range between 60% and 76% signal. For this task, the subjects require around 30-39 discs pairs out of a potential 50 pairs to detect structure at the 83% correct threshold. In the unknown axis condition, thresholds are obtained between 74% and 92% signal. The subjects therefore require between 38 and 47 discs pairs out of a potential 50 pairs to detect structure at the 83% correct threshold.

The psychometric functions from the variable and fixed axis conditions were compared and no significant differences were found for any of the subjects. It can be seen that although the thresholds are increased in the variable axis condition (by approximately 8 disc pairs for each subject), the overall shapes of the functions are similar, showing a relatively gradual deterioration in performance in both conditions.

The data from this experiment were compared with those from Experiment 7, to show the effect of varying disc size within symmetrically matched pairs. Only two subjects were common to both experiments. In the central axis condition subject LJM was found to be significantly poorer at detecting pairs of variable size across the middle range of stimulus levels ($p < 0.02$), however, no significant differences were found for the other subject. In the variable axis condition, no significant effect of varying disc size was found.

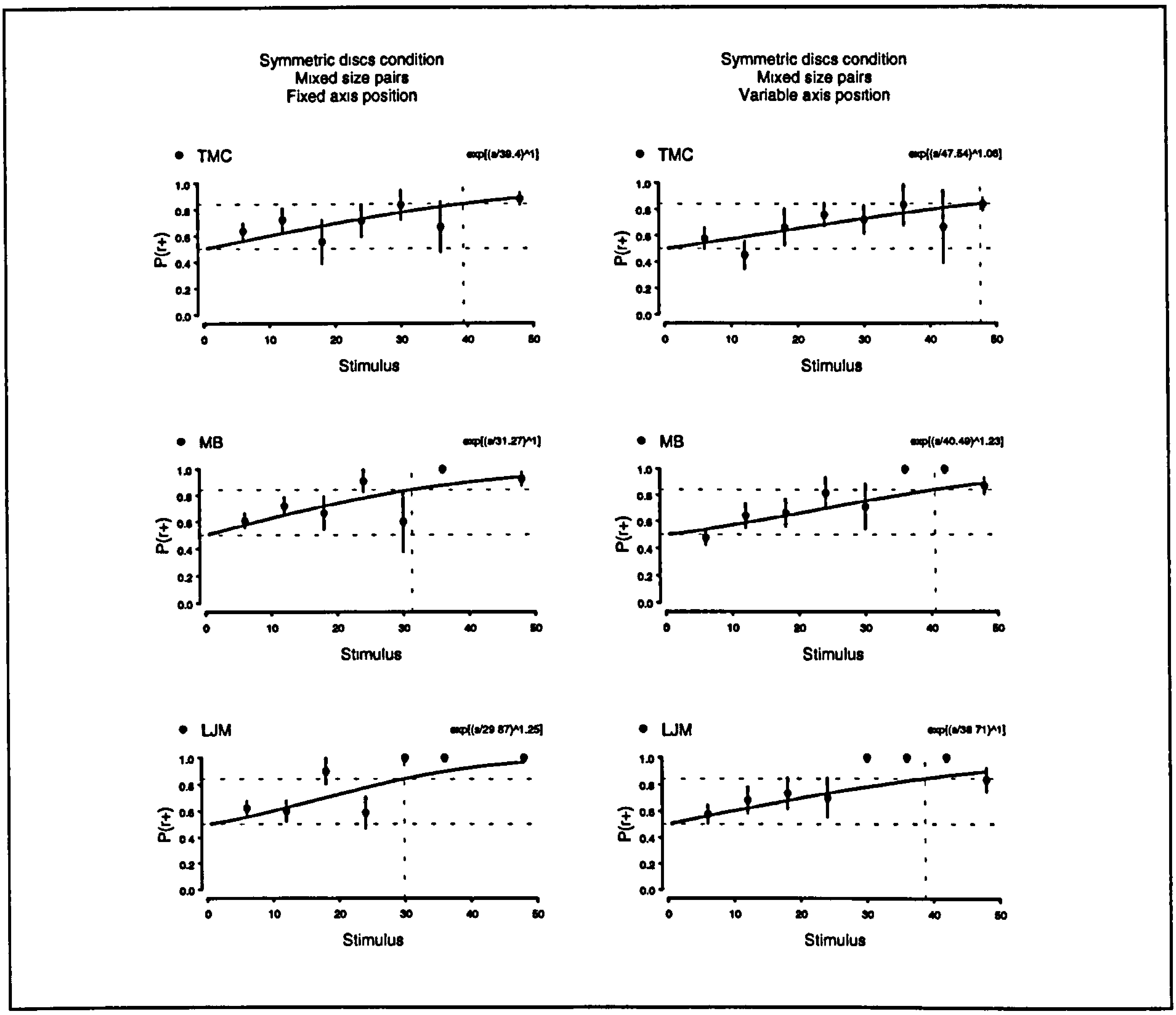


Figure 6.4. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

6.3.4 Discussion

The results of this experiment confirm the finding that axis position knowledge does not greatly effect detection of symmetric disc patterns, and that detection can therefore be considered presegmental.

Varying the size of the paired discs appears to cause some disruption of detection performance, nonetheless subjects are still able to detect structure under both fixed and variable axis conditions. It was hypothesised that a strategy which relies on accurate positioning and alignment of elements about an axis would be more severely disrupted by variation in the size of the elements (and the consequent misalignment of disc edges), than would a more global strategy, based on the detection of coarse symmetric structure. The slight effect of size, and the equivalent performance in both axis conditions supports the hypothesis that subjects are using global, and relatively coarse information to do this task.

The hypothesis is not fully tested here, as there is no experiment in which detection using a *known* local strategy is tested under conditions of mixed size elements. However, another way to determine the contribution of accurate element positioning to performance on this task, is to test performance under conditions where local position information is intact, but where global information would be expected to be disrupted. This is carried out in the following experiment, by varying luminance cues in the stimuli.

The logic for this comes from Experiment 6, in which it was found that under known axis conditions, symmetry could be detected in opposite contrast patterns, where dot position and alignment were the only cues by which to match. However, under unknown axis conditions, detection was severely disrupted by mixing dot contrast, indicating that global mechanisms are contrast dependent and that positional alignment alone is not sufficient to support global detection.

It is therefore possible to determine the extent to which subjects are using point position information in the discs experiments, by varying the intensity of the elements within, as well as between disc pairs. If local position information, and accurate element alignment is a useful cue to symmetry in the disc patterns, then symmetry detection should be preserved under conditions of varying intensity, as the local position information is preserved. However, if coarser, features, of uniform intensity are most useful in this task, (as predicted by Experiment 6), then poor performance would be expected under conditions of variable intensity.

6.4 Experiment 9 - The effect of varying grey level within pair matches

6.4.1 Introduction

It was established in Experiments 7 & 8 that for the disc stimuli, detection performance was less dependent upon knowledge of axis position than with the dot stimuli, but was dependent to an extent upon the paired elements being matched for size.

The purpose of this experiment was to determine whether subjects could detect structure in the disc patterns when the elements were matched for size, but not for intensity within matching pairs.

6.4.2 Method

Stimuli

The stimuli were identical to those in Experiment 7 with the exception that the grey levels of the matched discs were randomly selected from a range of ±120 grey levels. Sample stimuli are given in Figure 6.5.

Subjects

The subjects in this experiment were TMC, CBH, and LJM (see General Methods for subjects' details). Only one subject (TMC) completed both fixed and random axis conditions.

Task

The subject's task was to discriminate the target stimulus containing the symmetrically placed elements from the distractor stimulus containing only uncorrelated elements. Subjects were shown a number of sample stimuli to explain the task, which made clear the variation in disc intensity, the range of positions and the orientation of the target stimuli within the background window.

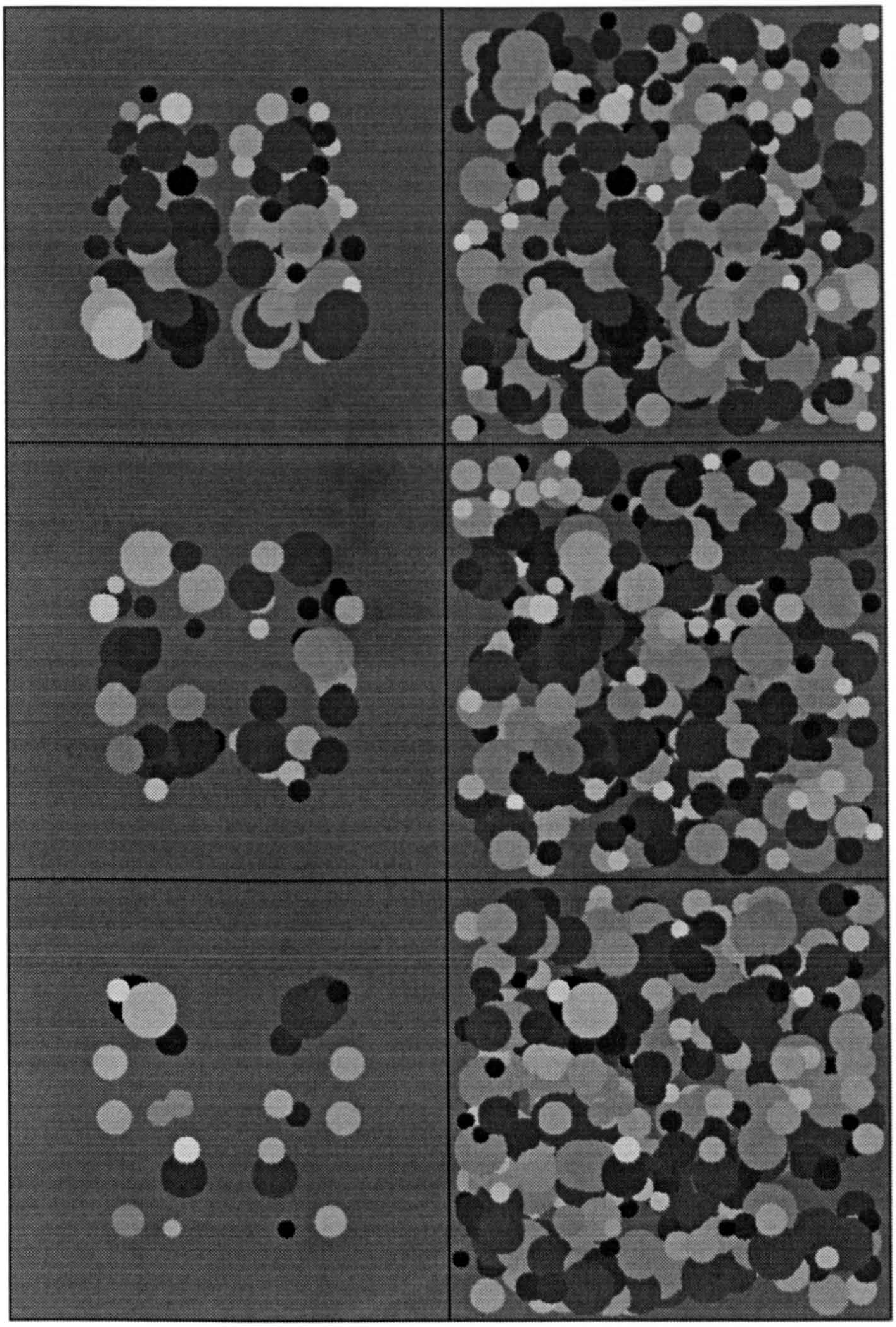


Figure 6.5. An example of the random disc symmetry pattern used in Experiment 9 (variable disc intensity). The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that disc size is matched within pairs, but disc intensity is variable both between and within matched pairs. In the random axis condition the position of the stimulus window was varied within the outer background window..

6.4.3 Results

Figure 6.6 shows the psychometric functions obtained from three subjects on this task in the known axis condition and one subject in the unknown axis condition. In both cases the detection performance fluctuates around the 50% correct point across the stimulus range. None of the subjects reached the 83% correct performance level in the fixed axis condition and so thresholds cannot be calculated for this task. Only one subject completed the variable axis condition and again, no threshold was obtained. The subjects could not reliably detect structure in these stimuli even at full signal. Note that the thresholds reported in Figure 6.6 are all above the maximum number of 50 disc pairs for this stimulus (100% signal) and are therefore effectively meaningless.

6.4.4 Discussion

The data from Experiment 9, reveal that reliable detection of the targets was impossible even at 100% stimulus under both central and random axis conditions. Detection of structure in these stimuli is therefore heavily dependent upon matched intensity between paired elements. The fact that detection was not possible even with prior knowledge of the axis position indicates that local position information is a very weak cue to the presence of structure in these patterns and that the structural information in these stimuli is carried by more global cues which are characterised by regions of similar contrast.

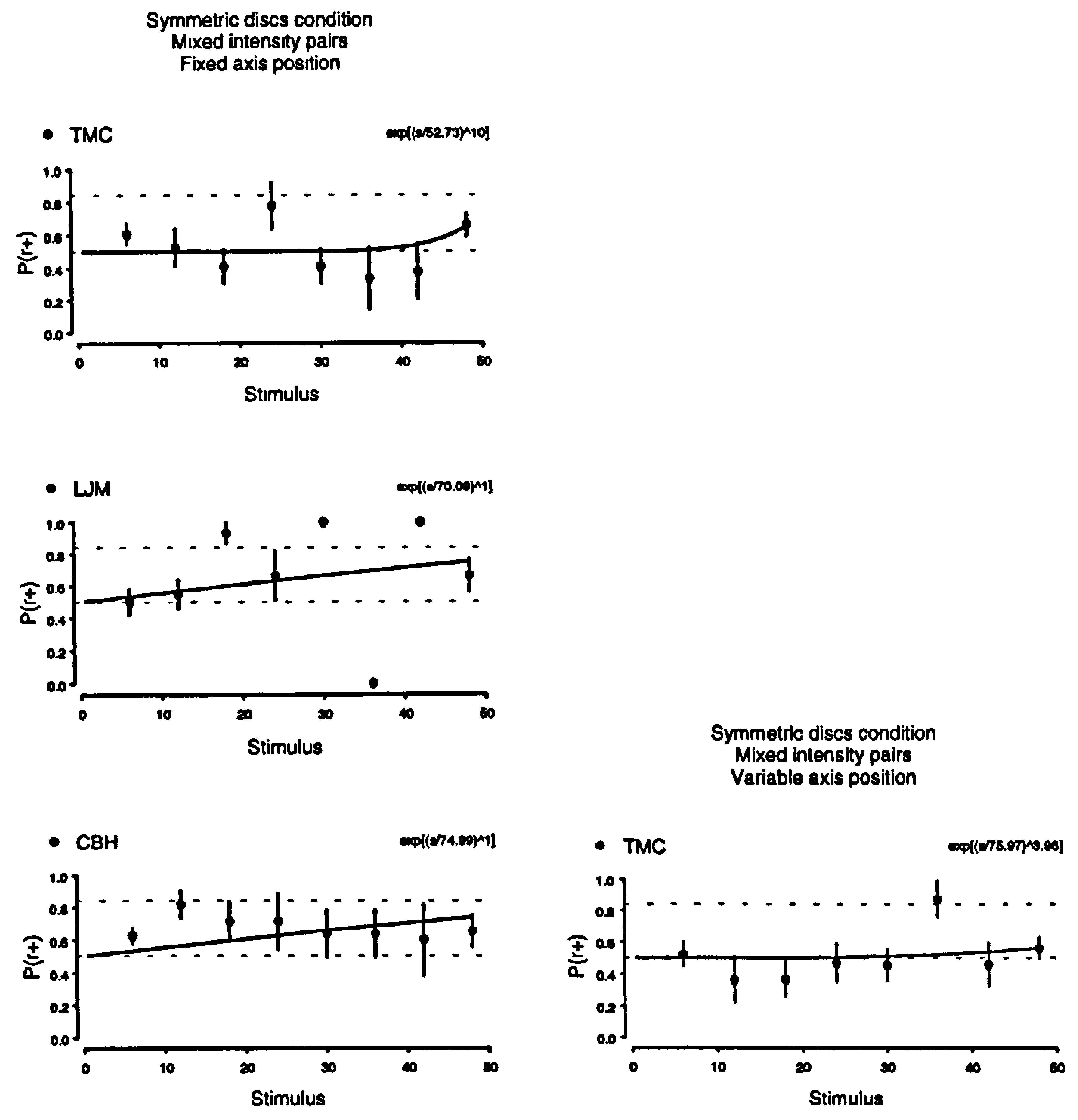


Figure 6.6. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects in the fixed axis condition, and 1 subject in the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The first figure given in brackets coresponds to the stimulus level at which the 83% correct threshold is obtained. These figures are all greater than 50 (the maximum number of dot pairs) indicating that no thresholds were obtained for this condition. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

6.5 General discussion

This series of experiments established that dense targets with visually distinctive elements are easily detected in a noise background. The visual factors that contribute to the high performance, are the matching size and more importantly, grey level of the paired elements. The fact that symmetry can be detected despite variation in the size of the discs, but not variation in intensity, indicates that highly accurate alignment of elements about the axis may not be the strongest contributing factor to the detection of structure in these stimuli, and reaffirms the finding of Chapter 5, that presegmental symmetry detection involves a relatively coarse scale detection of structure, denoted in part by regions of uniform contrast.

An additional visual factor which may contribute to detection performance in the symmetric disc stimuli is the obvious parallel structure which emerges in the patterns, particularly at the higher signal to noise ratios. The density of the signal and the differentiation between pairs by contrast, gives these stimuli a striated appearance which may provide a cue to global structure. It was noted in Experiment 8, in which the elements were varied in size but matched for contrast, that detection performance was variable across the stimulus range, and that this variability may be due to the presence of an uncontrolled variable which did not change consistently with stimulus level. It is possible that this additional variable was the strength of the observed parallel structure. The perceptual strength of the parallel structure in these stimuli is likely to vary as a function of a number of factors such as the distance between the elements, and as in Experiments 8 and 9, the difference in size and intensity of the paired elements, as well as the number of matched pairs present. These factors are investigated in the experiments in Chapter 7.

7

DETECTION OF PARALLEL STRUCTURE

7.1 Overview

The purpose of introducing the larger pattern elements of variable size and grey level in Chapter 6 was to investigate symmetry detection ability using stimuli which more closely emulate the perceptual qualities of natural visual scenes than perhaps do random dot patterns. It was established in these experiments that perception of structure was preserved despite variation in the size of elements within symmetric pairs, but that an essential condition for the perception of symmetric positioning of elements was that paired elements should be equal in contrast. This finding suggests that symmetrically positioned regions of similar intensity are readily correlated and that the resulting structure is perceived at a global level. The subjects were unable to detect symmetrically positioned elements solely on the basis of symmetric positioning and alignment.

This pattern of results raises the possibility that the global detection of symmetric structure depends, not on the detection of alignment of point pairs, but on secondary features which emerge from the symmetric pairings.

The possibility that the global structure is carried in the emergent features arising as a result of symmetry takes the issue away from the precise mathematical transformation which characterises symmetry, and towards the general force of symmetric structure in image segmentation and grouping. The natural symmetries which occur in our environment will rarely, if ever, conform to the mathematical definition of symmetry. Therefore, if secondary, or low-level features can be extracted from symmetric structure, which are also common to approximately symmetric structure, then it is possible that these are the features which support grouping and segmentation in natural images.

In the disc stimuli, the detection of structure appears to be mediated by luminance correlations across pairs of elements, which at a global level, appear collectively as a series of elongated features, aligned in parallel about a single axis. In the previous chapter it was pointed out that the perception of parallel structure may depend on a variety of stimulus factors, including the similarity of the elements and the separation between the elements in a group. The purpose of this series of experiments was to further investigate the perceptual components of parallel structure in the disc patterns.

7.2 Experiment 10 - Detection of parallel structure under central and random axis conditions.

7.2.1 Introduction

The effect of parallel structure on detection ability was measured in this first experiment by exaggerating the structure to varying extents. Parallel structure was enhanced by adding additional pattern elements along the horizontal ‘virtual’ line joining each symmetric pair. These additional elements were placed at irregular spatial intervals along the virtual line in order to disrupt the internal symmetry of the pattern, thereby disrupting as far as possible any local symmetry about the axis region. The effect of this was to create horizontal strings of elements, which were aligned about a vertical axis. This modification had the effect of enhancing the impression of horizontal striation in the stimuli, whilst breaking the perfect symmetry of the pattern. Subjects performance was measured at four string lengths, each under both fixed and variable axis conditions.

7.2.2 Method

Stimuli

The stimuli were generated as described in Experiment 7 with the exception that the symmetric targets contained strings of matching discs rather than pairs.

To create the strings, pairs of additional elements were placed along the virtual line joining the symmetric ‘parents’. The additional elements were identical to the parents. Although they were laid in pairs, the additional elements were not equidistant from the axis therefore the strings did not have internal symmetry. As the strings were orthogonal to the axis of symmetry, the targets appeared as a list of strings of blobs aligned about the axis.

Four string lengths were used in the experiment. Common to all of these was an outer pair of discs which were symmetrically placed about the axis. The symmetric pairs with no additional elements was taken to be a string of two elements. Strings of four, six and eight elements were generated by placing two, four, and six elements respectively along the virtual line between the parent pair.

In order that the presence of strings alone did not cue the target in the discrimination task, the distractor stimuli used in the experiment also contained strings. These were generated between randomly positioned discs in order to create strings of random position and orientation with respect to the axis. The noise targets thereby contained strings which were equal in number and length to those in the structured targets but which were not aligned with one another.

As the signal to noise ratio changed within the stimulus window structured strings were not replaced with random strings but with the equivalent number of uncorrelated single discs.

The strings themselves varied in appearance depending on the size of the discs and the distance between the initial pair. Some of the strings had the appearance of a row of small discrete elements, others merged together looking like a single elongated feature.

The stimulus windows were each embedded in a 300 by 300 pixel background which contained uncorrelated noise elements. The strings were at no point obscured by the noise.

The stimulus window was either positioned centrally in the background window or varied within the background window between trials. The only constraint on the axis position was that it should allow the entire target to fall inside the stimulus window. For each trial the axis position was randomly selected from the range of values which satisfied this criterion. The axis of symmetry was vertical in all trials. Sample stimuli are given in Figure 7.1.

Subjects

The subjects were TMC, LJM, LAW, and CBH (see General Methods for details).

Task

The subject's task was to discriminate the target display containing the symmetrically aligned strings, from the distractor which contained the non-aligned strings. Subjects were shown a number of sample stimuli to explain the task, which made clear the nature of the strings and the orientation and range of positions of the target stimuli within the background window.

Subjects were tested on four string lengths of 2, 4, 6, & 8 elements. The four string lengths were randomly interleaved in a single run of 256 trials. The trials were blocked by axis condition.

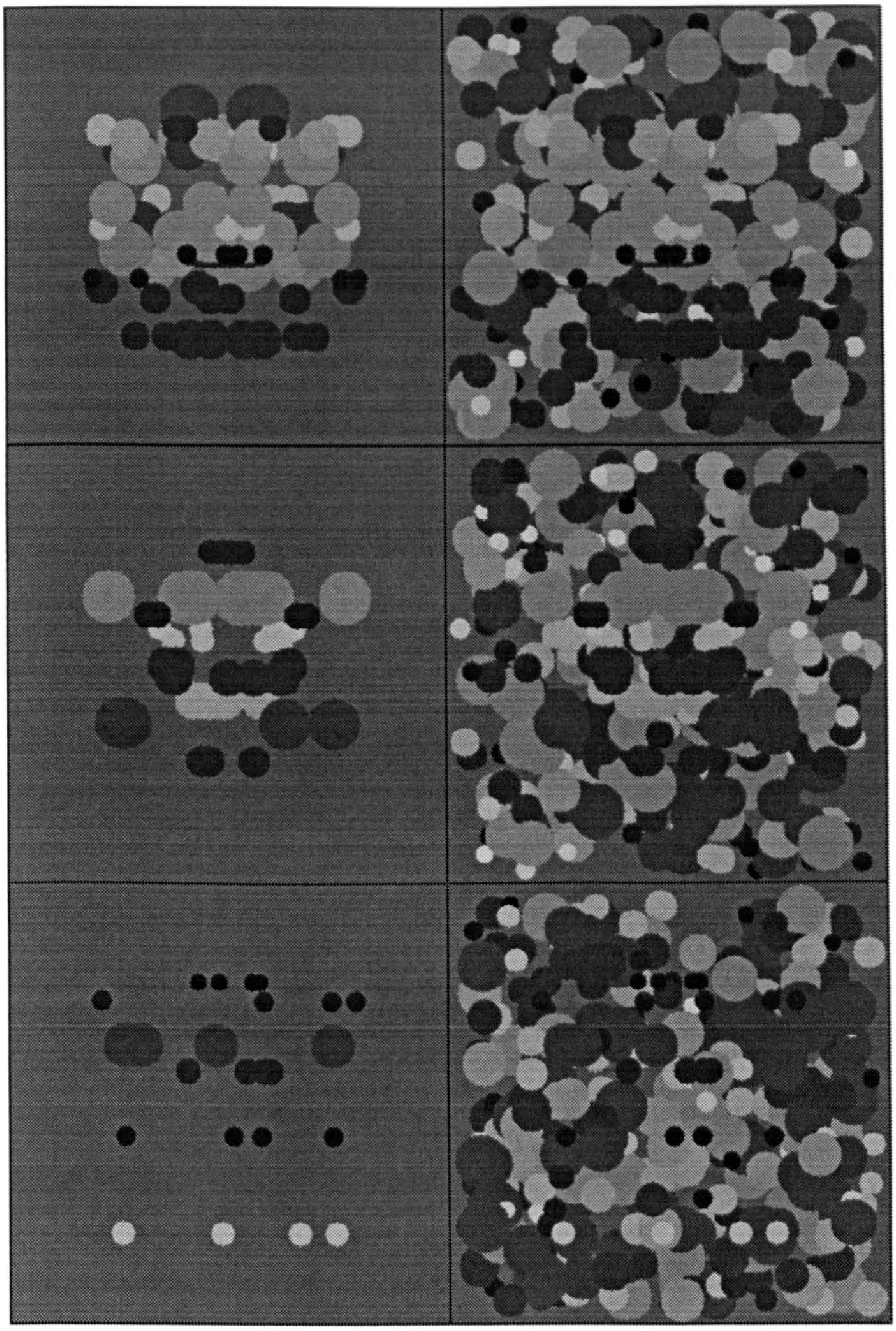


Figure 7.1a. An example of the disc strings pattern used in Experiment 10. String length of 4 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each symmetrically placed disc pair there are two randomly positioned additional elements, which sometimes occlude one another. It can be seen that disc size and grey level are matched within pairs, but vary between pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

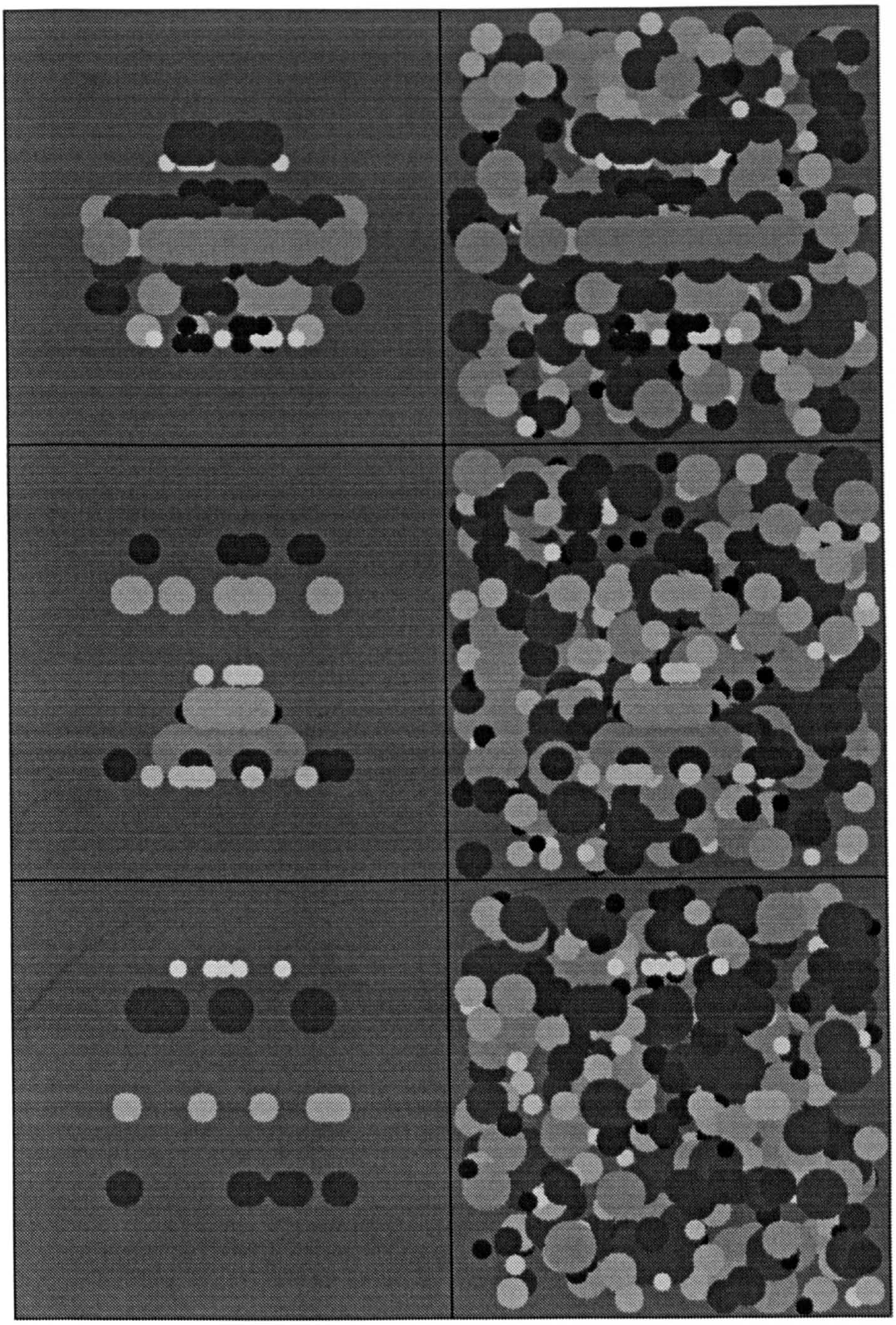


Figure 7.1b. String length of 6 is shown here. This figure is identical in nature to Figure 7.1a, except that within each symmetrically placed disc pair there are four randomly positioned additional elements.

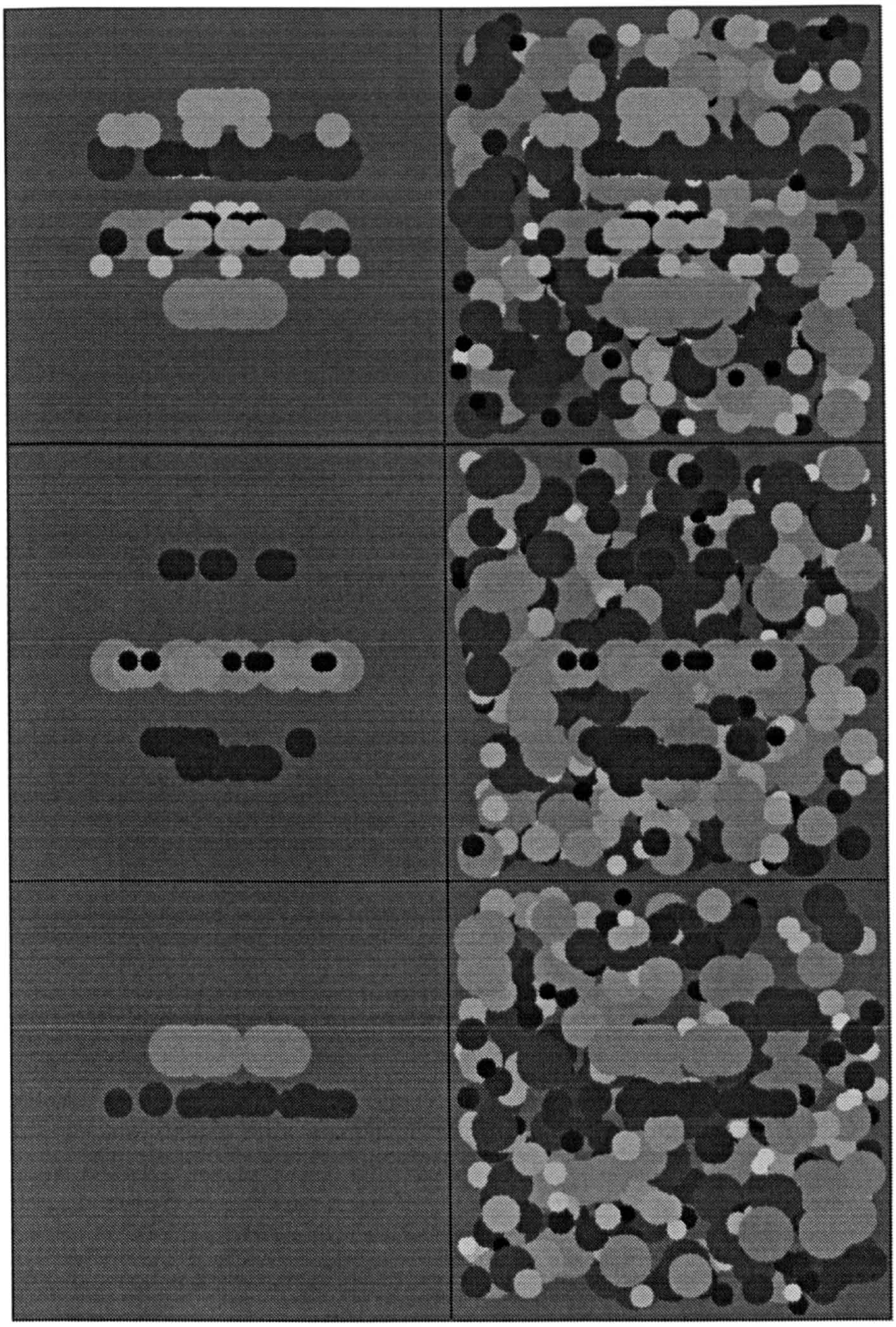


Figure 7.1c. String length of 8 is shown here. This figure is identical in nature to Figure 7.1a, except that within each symmetrically placed disc pair there are six randomly positioned additional elements.

7.2.3 Results

In Experiments 1-9, detection performance (and the salience of the targets) was measured by changes in the number of symmetric pairs required to detect symmetric structure at the 83% correct threshold. The calculation of detection thresholds for this experiment is less straightforward and the data can be presented in two possible ways. The first is to calculate the number of strings required for detection at the 83% correct threshold, and the second is to calculate the total number of signal elements required. However, these two methods of calculation can yield apparently different results. Given a maximum number of 100 signal elements, the proportion of total signal elements in each string is increased as string length increases. It is therefore possible that a reduction in the number of strings at threshold, (indicating an improvement in performance), would cause no alteration, or even an increase, in the total number of signal dots at threshold (indicating no change, or a decline, in performance). Thus, in such a case, the same data set would suggest different effects on detection performance depending on the method of calculation. Fortunately, this situation does not arise here to any significant extent, as both methods of calculation indicate similar patterns of performance on this task.

The number of strings, rather than the total number of disc elements was chosen as a measure of performance for two reasons. First, because the number of elements required at threshold is likely to be overestimated, particularly at the longer string lengths, due to the fact that the elements are frequently occluded by other identical elements. Second because the effect of parallel structure is of interest here, the number of parallel components required for detection seems to be a more meaningful measure of performance. The maximum number of possible strings in the stimulus is reduced as string length is increased, such that full signal is reached at 50, 25, 16, and 12 strings for lengths of 2, 4, 6, and 8.

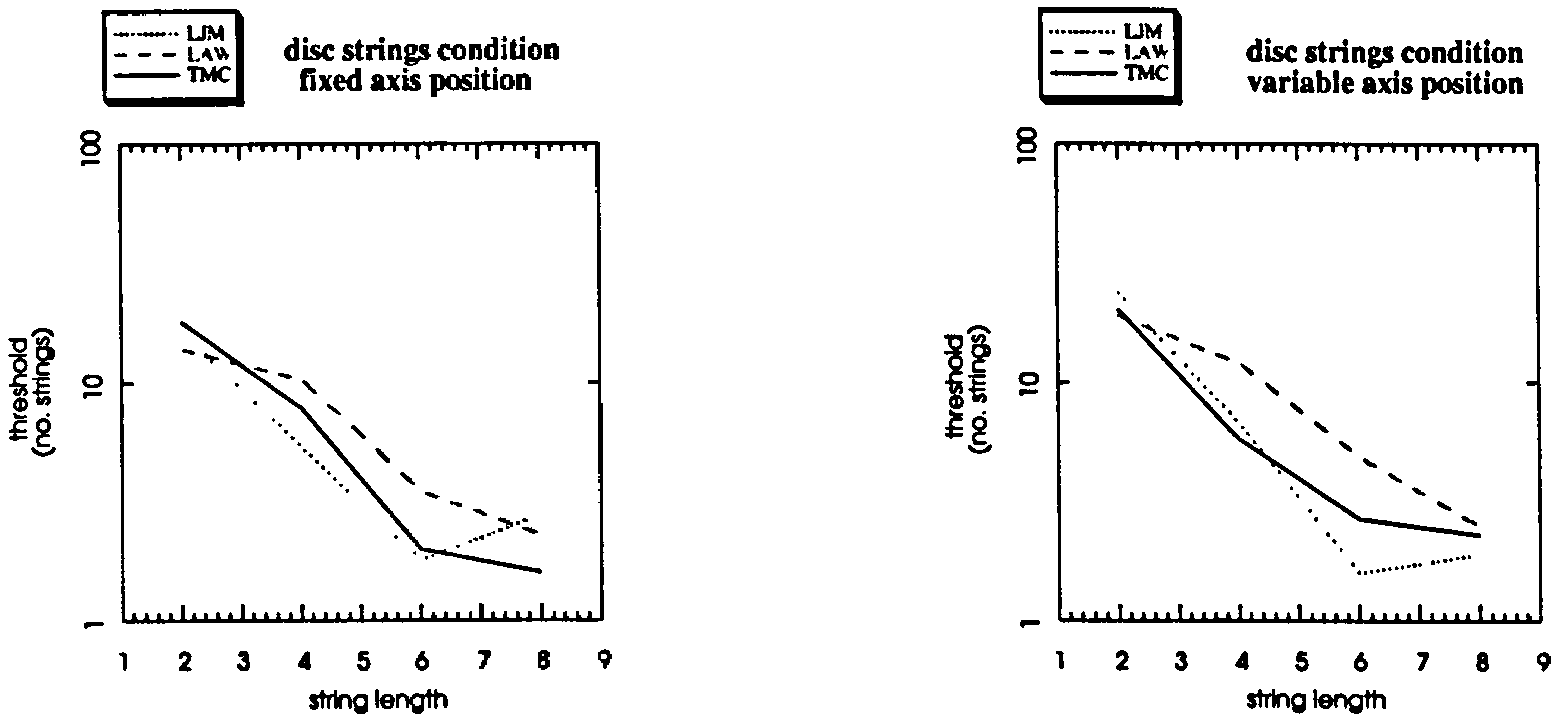


Figure 7.2. Graph to show detection thresholds as a function of string length for 3 subjects. Left-hand graph shows data from the fixed-axis condition; the right-hand graph shows data from the variable-axis condition. The ordinate is the number of strings required for detection at 83% correct level. Abscissa is the number of elements contained in the disc string. Each data point is the threshold from a single psychometric function, obtained by combining the data from three runs into a single function.

The data from this experiment are summarised in Figure 7.2., which shows the threshold number of strings as a function of string length for three subjects. There is an overall improvement in detection performance as string length is increased. In the known axis condition, the thresholds decrease from 13-17 strings of 2 elements, to only 2-3 strings of 8 elements, whilst in the unknown condition performance improves from 19-24 strings to only 2-3 strings, for 2 and 8 elements respectively. In general, performance improves most rapidly with the increase in string length from 2 to 6 elements. A floor effect is beginning to be reached at 6 to 8 elements, at which point many of the matched pairs have merged with the additional elements to form solid elongated structures. The addition of further discs will have no visual effect on these structures.

The psychometric functions for this condition are presented in Appendix A. The functions show the characteristic shape of a gradual increase in slope as the stimulus level is increased, becoming shallow or flat at high stimulus levels. It can be seen that the shape of the psychometric functions is similar across axis condition, suggesting that there is no large effect of prior knowledge of axis condition in this experiment. The slope of the functions does however increase as a function of string length.

Psychometric functions from the fixed and variable axis conditions were compared for each string length. With the exception of one subject at string length of 6, no significant differences were found between the two axis conditions. There is no obvious explanation for the single significant difference found (LAW, $p < 0.018$), and, given the trend in the rest of the data, the difference found is probably not meaningful.

Data were also compared between the different string lengths (variable axis condition). The improvement in performance as a result of increasing string length from 2-4 elements was found to be significant for all three subjects (LAW, $p < 0.008$; LJM, $p < 0.03$; TMC, $p < 0.004$).

A significant improvement in performance was also found for two subjects between 6 and 8 elements (LAW, $p < 0.01$), but not for the other two subjects. This data confirms the beginning of a floor effect at string length 8.

7.2.4 Discussion

The results of this experiment suggest that perception of structure is improved by the enhancement of the parallel features in the pattern, despite the fact that this simultaneously disrupts the perfect bilateral symmetry in the pattern. Given the effects of strengthening the parallel structure in the stimuli it is of interest to establish whether this structure overrides the detrimental effect on performance of varying the size and grey level of the correlated elements as found in Experiments 9 and 10 or whether the perception of the structure is dependent upon these stimulus factors. The effects of element size and grey level are investigated in Experiments 11 and 12.

The strong facilitating effect of the string elements on the detection of structure raises some further questions about the perceptual cues which are present in the stimuli. Two low-level stimulus factors are combined in the parallel structure described in these stimuli; the elongation of symmetrically positioned features and the alignment of these features about a single axis. A clear effect of string length was found in these experiments, showing that the elongation of features is important in the detection of structure, however, because all of the stimuli were generated around a skeleton symmetric structure, the strings were always perfectly aligned about a midline axis. Given that the focus of the research has shifted from the perception of symmetry to the perception of 'symmetry-like structures', it is of interest to determine whether perfect alignment about a midline axis is required for the perception of structure, or whether a relatively compact series of elongated features is sufficient for this purpose. This question is investigated in Experiment 14.

A second question which must be addressed is the extent to which the subjects prior knowledge of axis orientation affects both the performance on this task, and the strategies used in detection of the targets. The results of this experiment show that at string lengths of 6 and 8 elements, subjects are able to reliably detect the presence of as few as two strings. In these cases, there is very little parallel structure present in the stimuli, and, given that the axis orientation is fixed in the patterns, it is possible that subjects may be preferentially responding to horizontal structure, rather than global structure in these stimuli. Given that the main focus of this thesis is concerned with the detection of structure in the absence of high-level knowledge of this kind, it is important to determine whether structure can be detected in these stimuli, in the absence of external cues to the orientation of the patterns. The effect of varying axis orientation is investigated in Experiment 15.

7.3 Experiment 11 - The effect of varying disc size on the perception of parallel structure.

7.3.1 Introduction

The purpose of this experiment was to determine the importance of disc size in the detection of parallel structure in these stimuli, by measuring subjects ability to detect structure in disc strings stimuli of varying size under known and uncertain axis conditions.

7.3.2 Method

Stimuli

The stimuli were identical to those in Experiment 10 except that the sizes of the discs (including the outer two discs) along the string were randomly selected from a range of 18 - 60 pixels (0.06 deg and 0.18 deg) in diameter. The discs along each string were matched for grey level. Again, performance was measured under both central and random axis conditions. Sample stimuli are shown in Figure 7.3.

Subjects

The subjects in this experiment were TMC, MB, and LJM (see General Methods for subjects' details).

Task

The subject's task was to discriminate the target stimulus containing the symmetrically aligned strings from the distractor stimulus containing the non-aligned strings. Subjects were shown a number of sample stimuli to explain the task, which made clear the nature of the strings, the variation in disc sizes, the range of positions and the orientation of the target stimuli within the background window.

Subjects were tested on four string lengths of 2, 4, 6, & 8 elements. The four string lengths were randomly interleaved in a single run of 256 trials. The trials were blocked by axis condition.

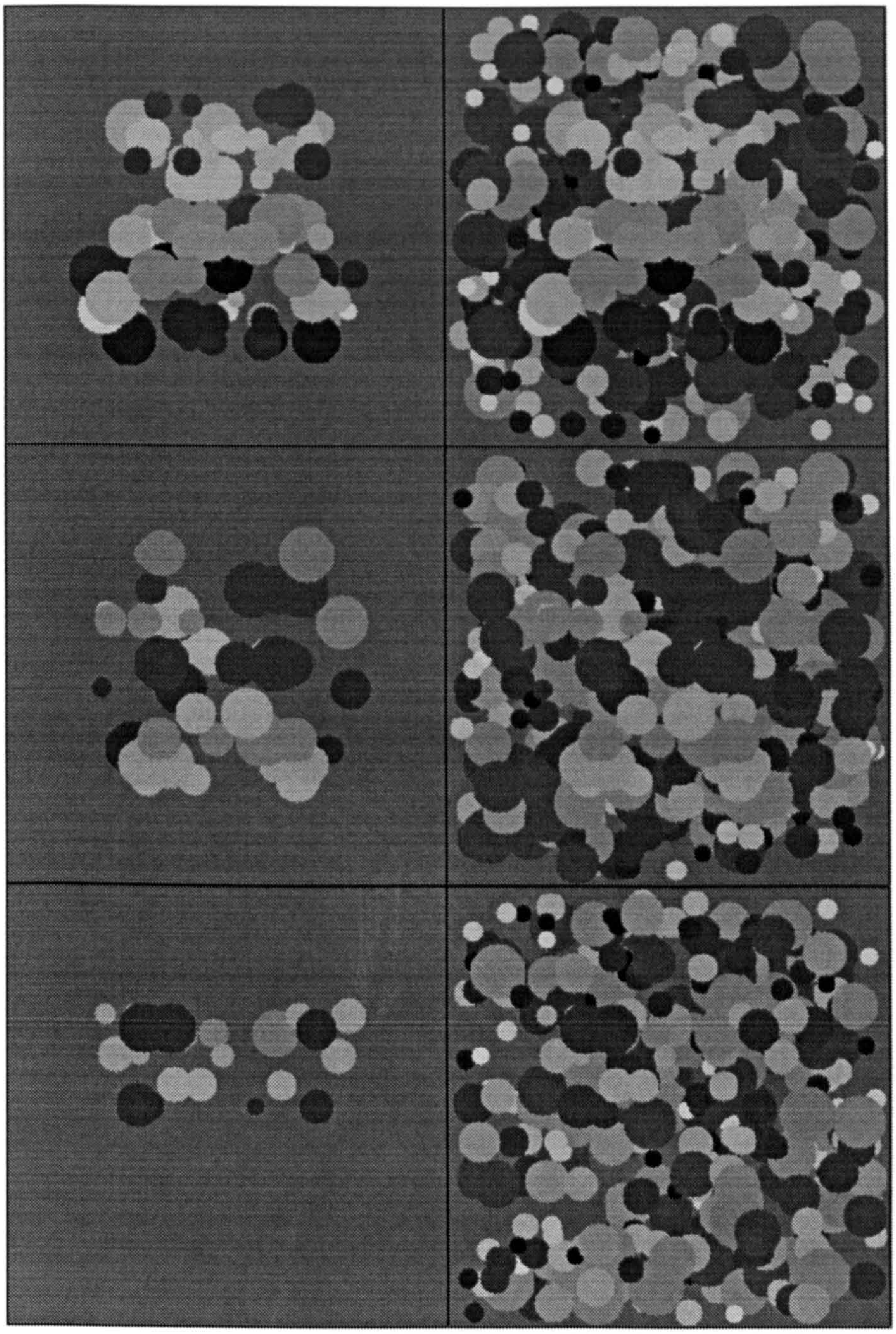


Figure 7.3a. An example of the disc strings pattern used in Experiment 11 (strings of variable disc size). String length of 4 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each symmetrically placed disc pair there are two randomly positioned additional elements, which sometimes occlude one another. Disc intensity is matched within pairs, but disc size is variable both between and within matched pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

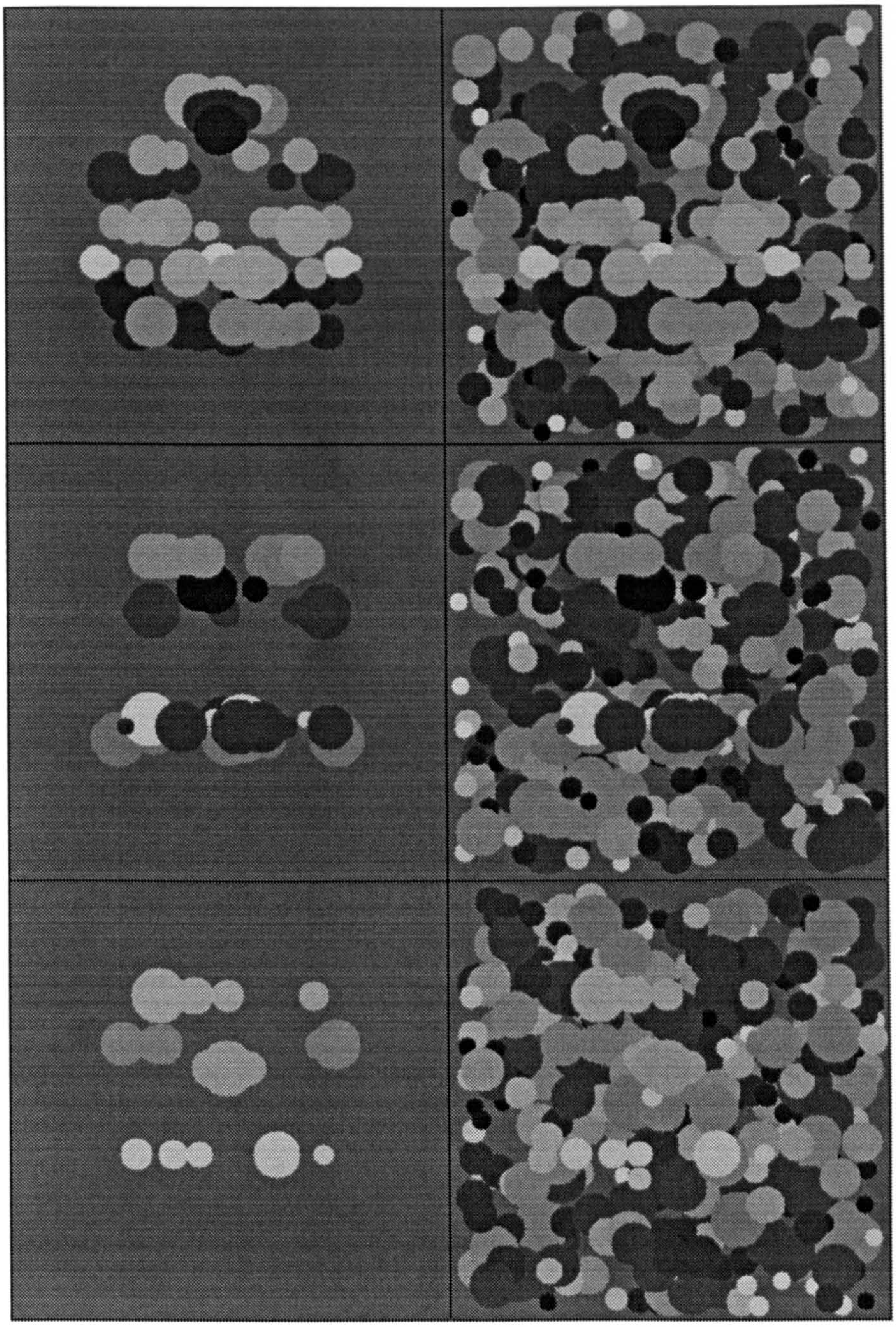


Figure 7.3b. An example of the disc strings pattern used in Experiment 11 (strings of variable disc size). String length of 6 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each symmetrically placed disc pair there are four randomly positioned additional elements, which sometimes occlude one another. Disc intensity is matched within pairs, but disc size is variable both between and within matched pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

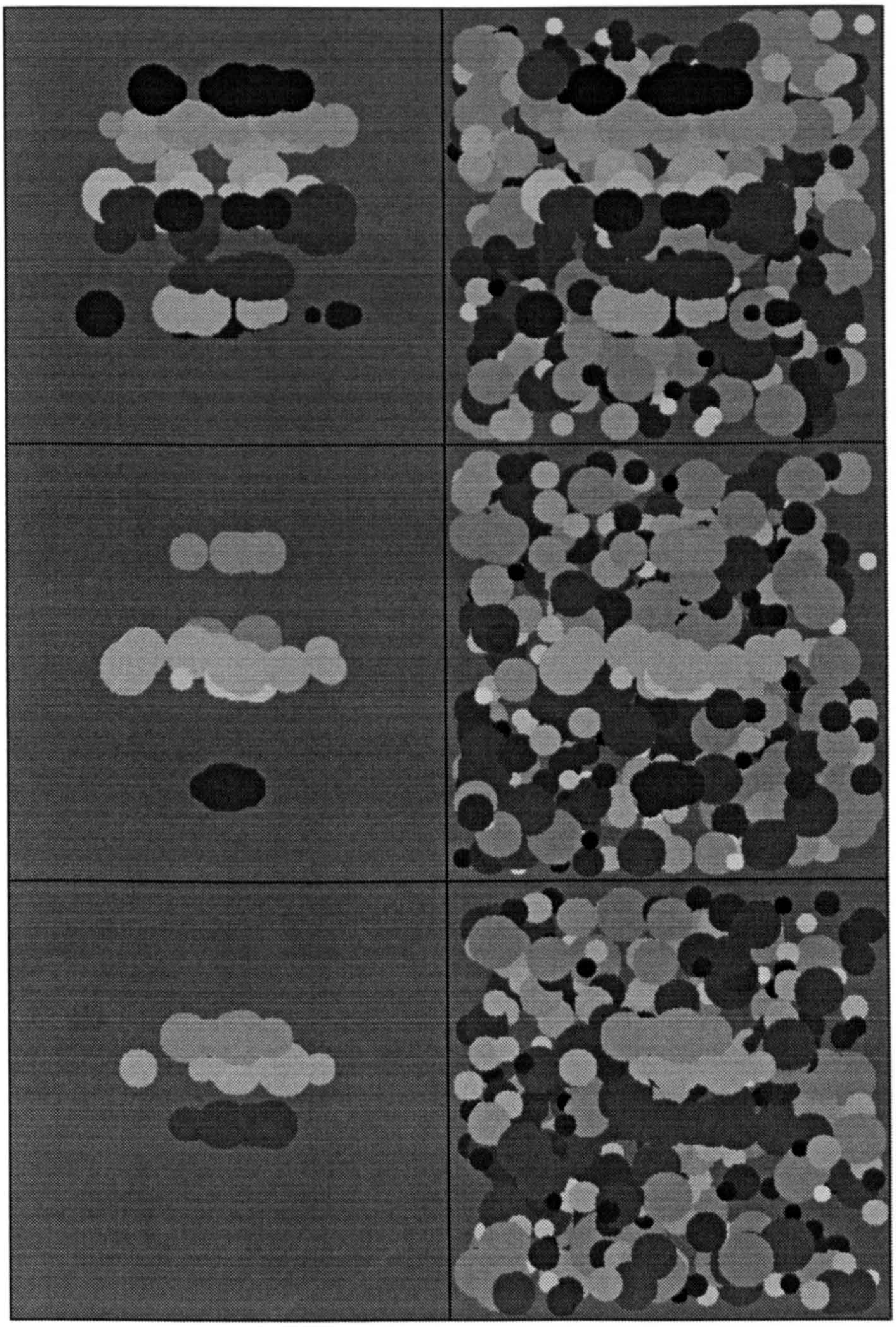


Figure 7.3c. An example of the disc strings pattern used in Experiment 11 (strings of variable disc size). String length of 8 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each symmetrically placed disc pair there are six randomly positioned additional elements, which sometimes occlude one another. Disc intensity is matched within pairs, but disc size is variable both between and within matched pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

7.2.3 Results

The data are summarised in Figure 7.4., which shows the threshold number of strings as a function of string length for three subjects. The given threshold measurements represent the number of strings required to detect the target stimuli at the 83% correct point.

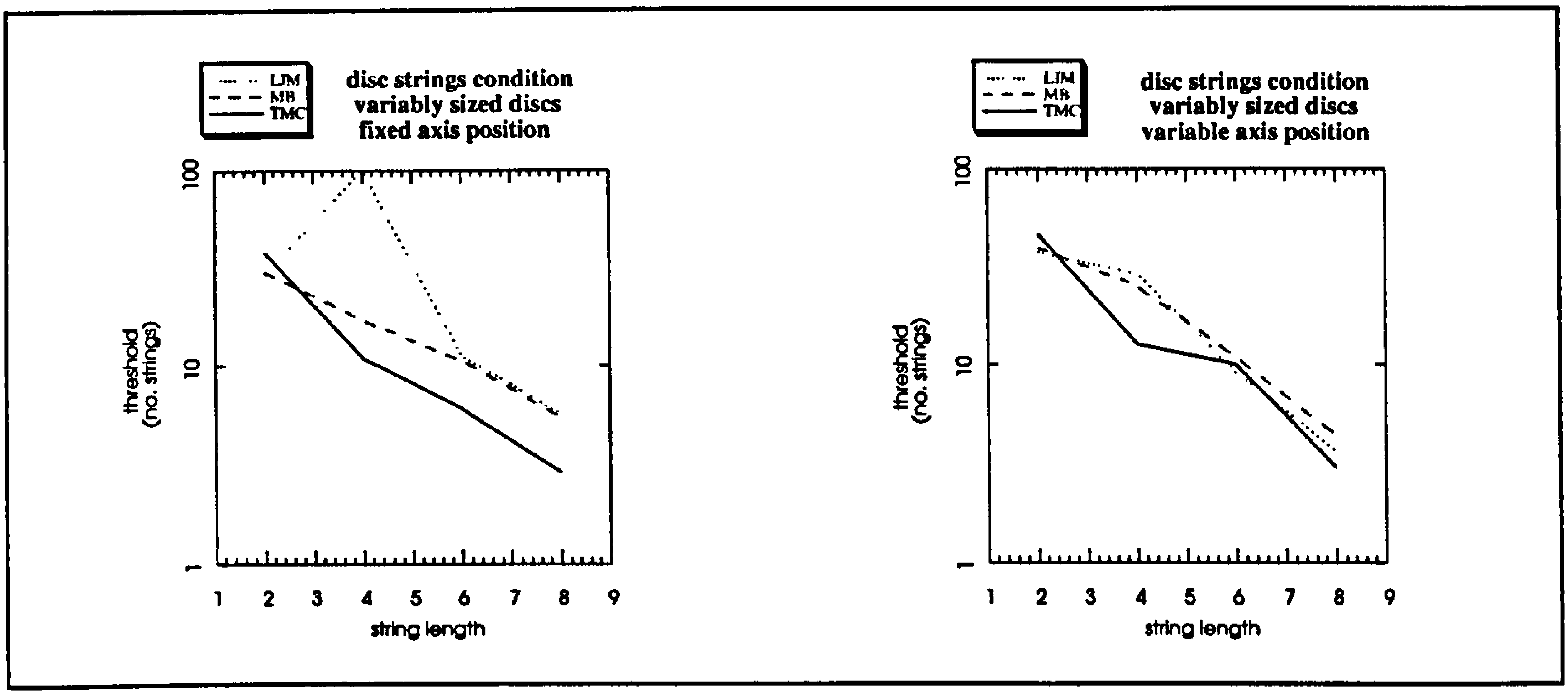


Figure 7.4. Graph to show detection thresholds as a function of string length for 3 subjects. The ordinate is the number of strings required for detection at 83% correct level. Abscissa is the number of elements contained in the disc string. Each data point is the threshold from a single psychometric function, obtained by combining the data from three runs into a single function.

There is an overall improvement in detection performance as string length is increased. In the central axis condition, detection thresholds are reduced from 30-38 strings of 2 elements, to only 3-6 strings of 8 elements. A similar improvement in performance is found in the variable axis condition, as the number of strings required for detection fell from 37-47 strings to 3-4 strings. One subject (LJM) did not achieve threshold performance at length 4 elements in the central axis condition, and the data point is arbitrarily set to 100 to indicate that no threshold was obtained.

The psychometric functions for each subject at the 4 string lengths are presented in Appendix B. Except perhaps at the longest string length, the psychometric functions from this condition tend to be uniform in shape, rather than the characteristic step shape found in the previous experiment. Detection performance tends not to reach 100% correct at the highest stimulus levels, suggesting that varying the size of the elements in the strings causes a slight, but systematic disruption of performance across the stimulus range and across string length.

Psychometric functions from the fixed and variable axis conditions were compared, and no significant differences between the two conditions were found at any of the string lengths, except at string length 4 where the subject failed to obtain a threshold. Prior knowledge of the axis position has no effect on detection performance in this experiment.

7.3.4 Discussion

Comparing these results with those of the previous experiment it can be seen that varying the size of the elements in the string is disruptive to detection performance. The psychometric functions show more variability in performance across the stimulus range than those in Experiment 10, and there is more variability in the threshold measurements, however the targets are nonetheless detectable, and there is a clear improvement in performance as a result of increasing string length.

The overall improvement in performance with increasing string length, in combination with the absence of an effect of axis knowledge, suggests that at the longer string lengths subjects may be detecting the global structure in the stimulus patterns.

There is some evidence in the shape of the discrimination functions that the global structure is somewhat disrupted by the variation in element size. In comparison with the strings of identical discs in which perfect detection was sustained across a considerable reduction in signal to noise ratio, performance declines rapidly in this condition as the cue is reduced from 100% signal. This more immediate decline in performance suggests that strings of variably sized discs are more difficult to detect than the regular strings even at high or full signal, and therefore that there is a slight effect of the size variation on global detection of the targets.

The results of this experiment indicate that the mechanism involved in detection of these structures is somewhat dependent upon regularly sized pattern elements, but is tolerant to some variation. However, although detection of structure is not entirely independent of disc size, the effects of varying the size are compensated by the strengthening of the parallel structure. Given this result it was of interest to find whether detection of the string stimuli was disrupted as severely by varying intensity as was found with the disc pairs, or whether this effect would also be overridden by the strengthening of the orthogonal structure. The effect of varying the intensity of the discs along the string was investigated in Experiment 12.

7.4 Experiment 12 - The effect of varying disc intensity on the perception of parallel structure.

7.4.1 Introduction

The purpose of this experiment was to determine the role of contrast in the detection of parallel structure in these stimuli, by measuring subjects ability to detect structure in disc strings stimuli of varying grey level under both known and uncertain axis conditions.

7.4.2 Method

Stimuli

The stimuli were identical to those in Experiment 10 except that the intensity of the discs (including the outer two discs) along the string were randomly selected from a range of ±120 grey levels. Within each string the discs were evenly sized. Performance was measured under both fixed and variable axis positions for one subject, however detection performance was poor under both conditions and thereafter, subjects were only tested with the fixed axis stimuli. Sample stimuli are presented in Figure 7.5.

Subjects

The subjects in this experiment were TMC, CBH, and LJM (see General Methods for subjects' details).

Task

The subject's task was to discriminate the target stimulus containing the symmetrically aligned strings from the distractor stimulus containing the non-aligned strings.

Subjects were shown a number of sample stimuli to explain the task, which made clear the nature of the strings, the variation in intensity along the string, the position and the orientation of the target stimuli within the background window.

Subjects were tested on four string lengths of 2, 4, 6, & 8 elements. The four string lengths were randomly interleaved in a single run of 256 trials. The trials were blocked by axis condition.

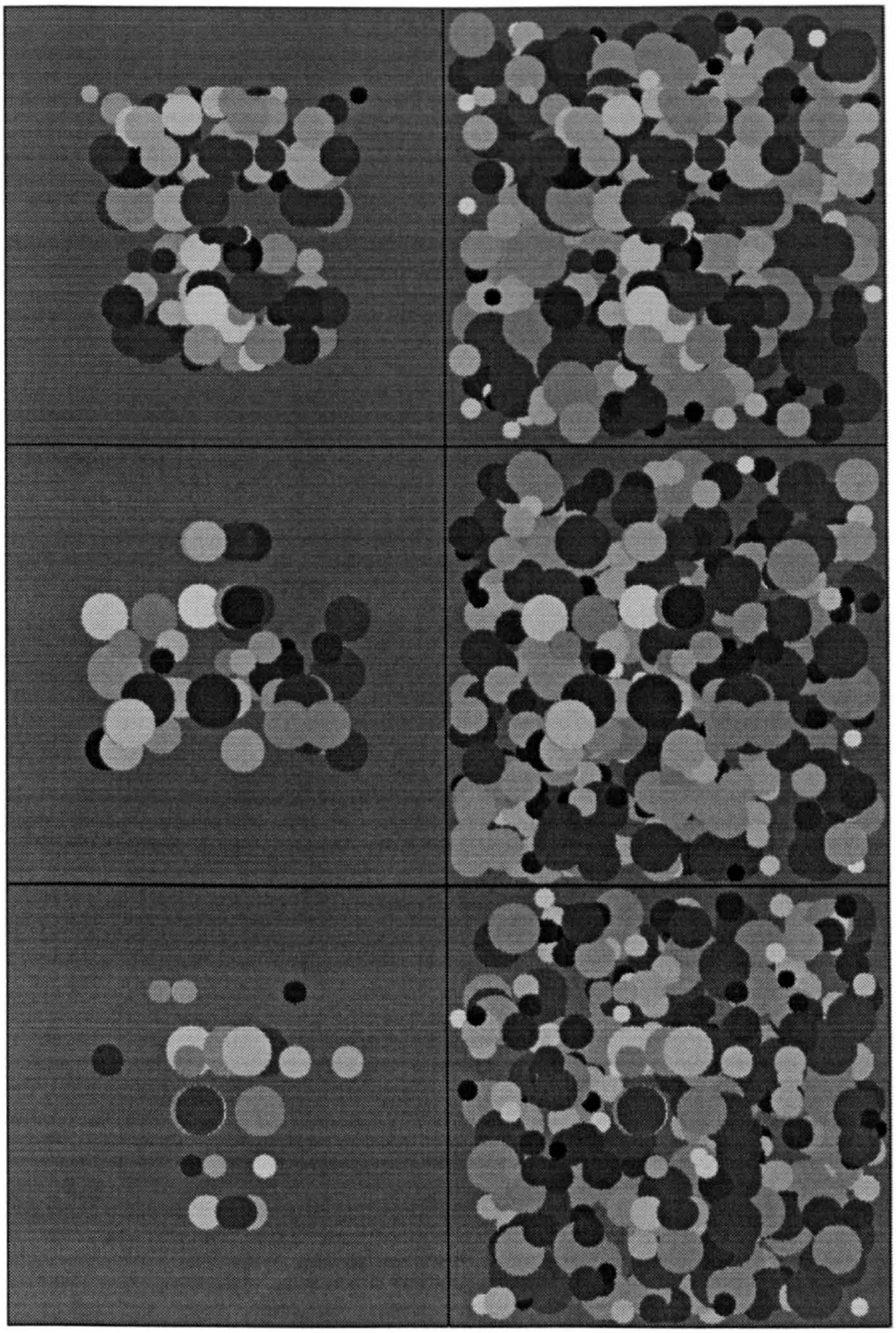


Figure 7.5a. An example of the disc strings pattern used in Experiment 12 (strings of variable disc intensity). String length of 4 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each symmetrically placed disc pair there are two randomly positioned additional elements, which sometimes occlude one another. Disc size is matched within pairs, but disc intensity is variable both between and within matched pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

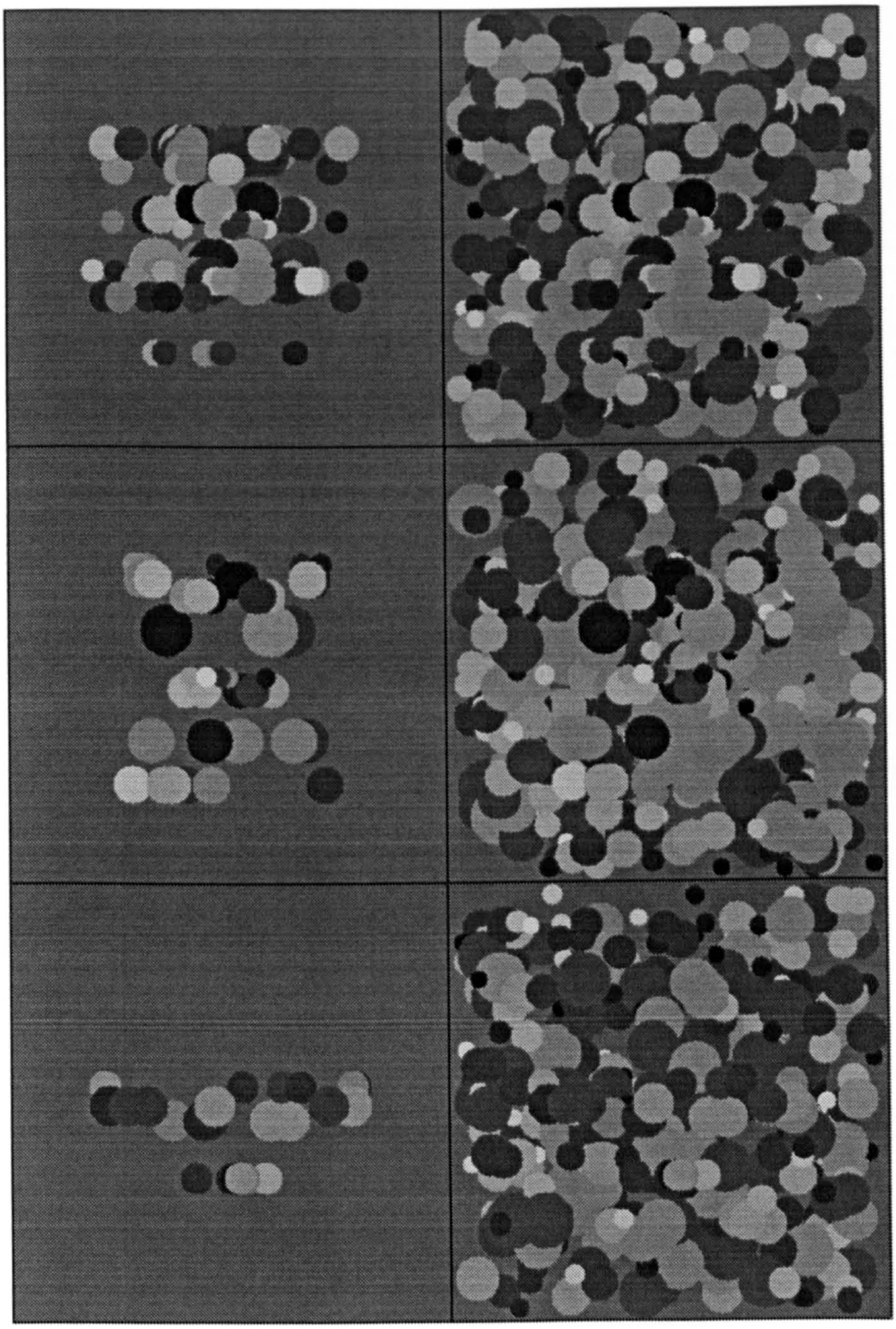


Figure 7.5b. An example of the disc strings pattern used in Experiment 12 (strings of variable disc intensity). String length of 6 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each symmetrically placed disc pair there are four randomly positioned additional elements, which sometimes occlude one another. Disc size is matched within pairs, but disc intensity is variable both between and within matched pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

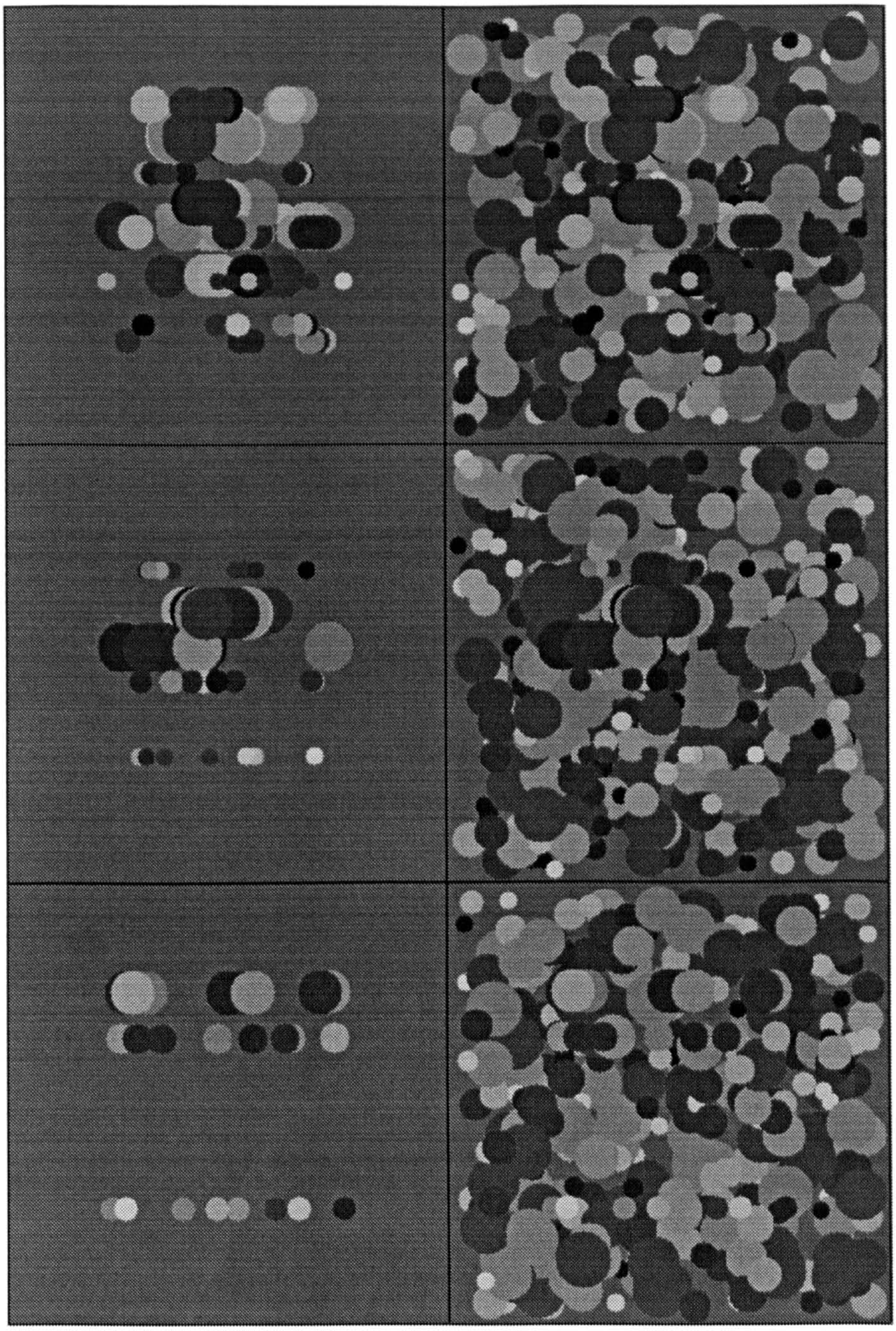


Figure 7.5c. An example of the disc strings pattern used in Experiment 12 (strings of variable disc intensity). String length of 8 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each symmetrically placed disc pair there are six randomly positioned additional elements, which sometimes occlude one another. Disc size is matched within pairs, but disc intensity is variable both between and within matched pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

7.4.3 Results

The psychometric functions for this experiment are presented in Appendix C. The data from this experiment are not summarised due to the fact that only one subject reached threshold performance level at one string length, therefore only one data point was obtained. Subject (LJM) reached threshold performance at string length of 8 in the central axis condition at 100% signal, but detection was otherwise impossible. The detection of structure is severely disrupted by variation in grey level within each string.

7.4.4 Discussion

The results of this experiment reveal that targets which vary in intensity within strings of elements are virtually impossible to detect. The intensity of the matching elements is a crucial determinant of detection performance, more so than the size of the elements. The perception of parallel structure in these stimuli is highly dependent upon the equal intensity of the correlated pattern elements.

Given the conditions for optimal detection of orthogonal structure in the disc stimuli (uniform size and uniform grey level along aligned strings) it was of some interest to determine whether enhanced parallel structure would improve detection performance in random dot stimuli, as dot strings would equally satisfy the conditions of uniform size and grey level. The effect of adding extra aligned elements to symmetric pairs of dots was investigated in Experiment 13.

7.5 Experiment 13 - The effect of parallel structure in random dot patterns

7.5.1 Introduction

In Experiment 10 it was established that detection performance improved as a result of strengthening the orthogonal structure in the symmetric stimuli.

The aim of this experiment was to determine whether a similar effect would be found if additional dots were laid between symmetric pairs in standard dot stimuli. Since the dot stimuli show very little parallel structure when in pairs, except in those pairs which are very closely matched, it was predicted that the presence of dot strings in the target stimuli would cause a marked improvement in detection performance.

7.5.2 Method

Stimuli

The stimuli in this experiment contained 200 symmetric and noise dots in varying SNRs. The stimulus windows measured 200 by 200 pixels and the stimuli were comprised of identical small black square dots arranged into strings of varying length. In this experiment, however, the dots did not overlap.

To create the strings, pairs of additional elements were placed along the virtual line joining the symmetric 'parents'. Although they were laid in pairs the additional elements were placed in random places along the string therefore the strings did not have internal symmetry. As the strings were orthogonal to the axis of symmetry, the targets appeared as a set of strings of dots aligned about the axis.

In order that the presence of strings alone did not cue the target in the discrimination task, the distractor stimuli in this experiment also contained strings. These were generated between randomly positioned dots in order to create strings with random position and orientation with respect to the axis. The noise targets thereby contained strings which were equal in number and length to those in the structured targets but which were not aligned.

As the signal to noise ratio changed within the stimulus window structured strings were not replaced with random strings but with the equivalent number of uncorrelated dots.

The stimulus windows were embedded in a 300 by 300 pixel background which contained uncorrelated noise dots in the region surrounding the stimulus window. The stimulus and background windows were balanced for dot density. The stimulus window was either positioned centrally in the background window, or varied within the background window between trials. The only constraint on the axis position was that it should allow the entire target to fall inside the stimulus window. For each trial the axis position was randomly selected from the range of values which satisfied this criterion. The axis of symmetry was vertical in all trials. Sample stimuli are shown in Figure 7.7.

Subjects

The subjects in this experiment were TMC, EMC, and LJM (see General Methods for subjects' details).

Task

The subject's task was to discriminate the target stimulus containing the symmetrically aligned strings from the distractor stimulus containing the non-aligned strings.

Subjects were shown a number of sample stimuli which to explain the task, which made clear the nature of the strings and the orientation and range of positions of the target stimuli within the background window.

Subjects were tested on four string lengths of 2, 4, 6, & 8 elements. The four string lengths were randomly interleaved in a single run of 256 trials. The trials were blocked by axis condition.

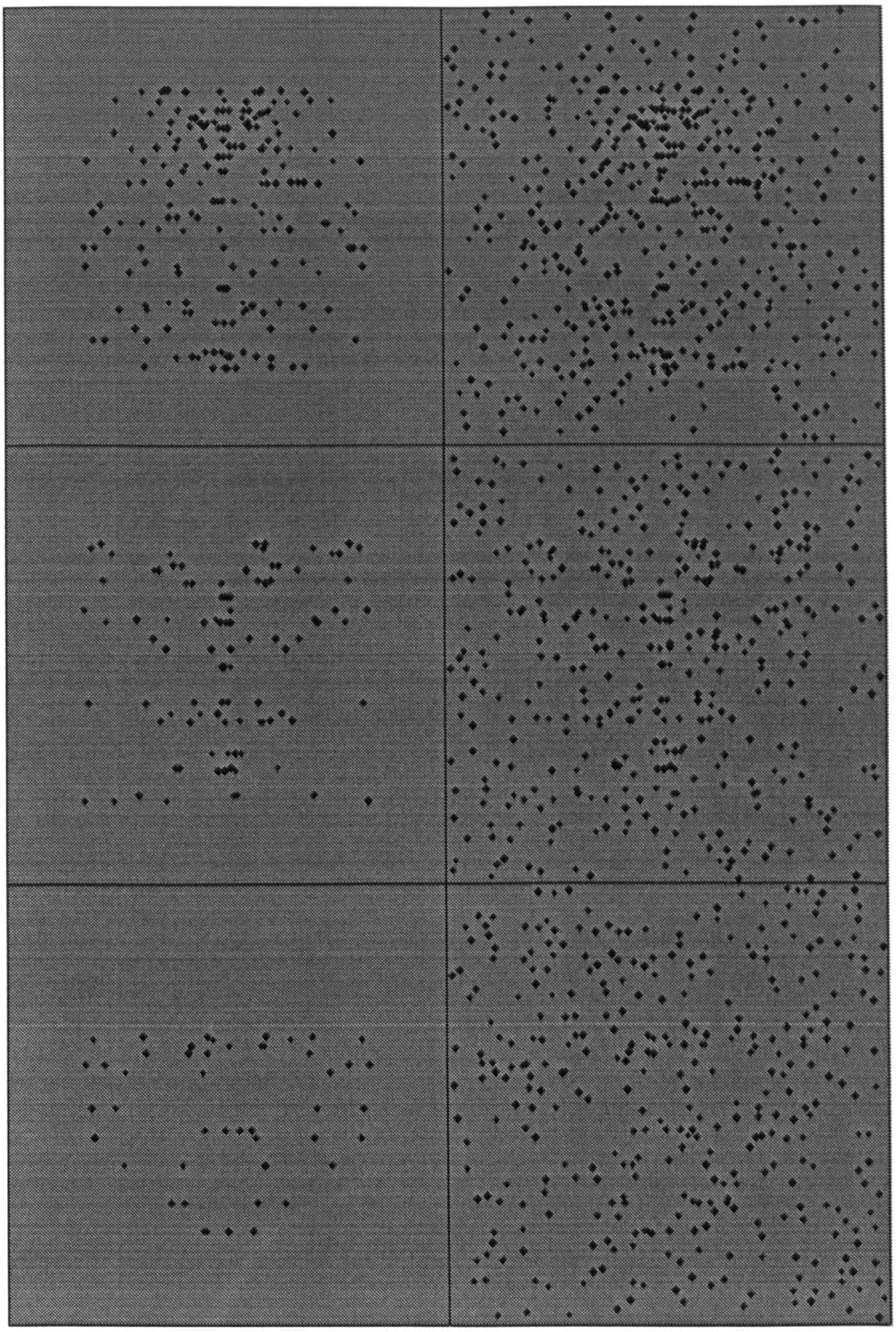


Figure 7.7a. An example of the random dot strings pattern used in Experiment 13. String length of 4 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each symmetrically placed dot pair there are two randomly positioned additional elements. In the random axis condition the position of the stimulus window was varied within the outer background window.

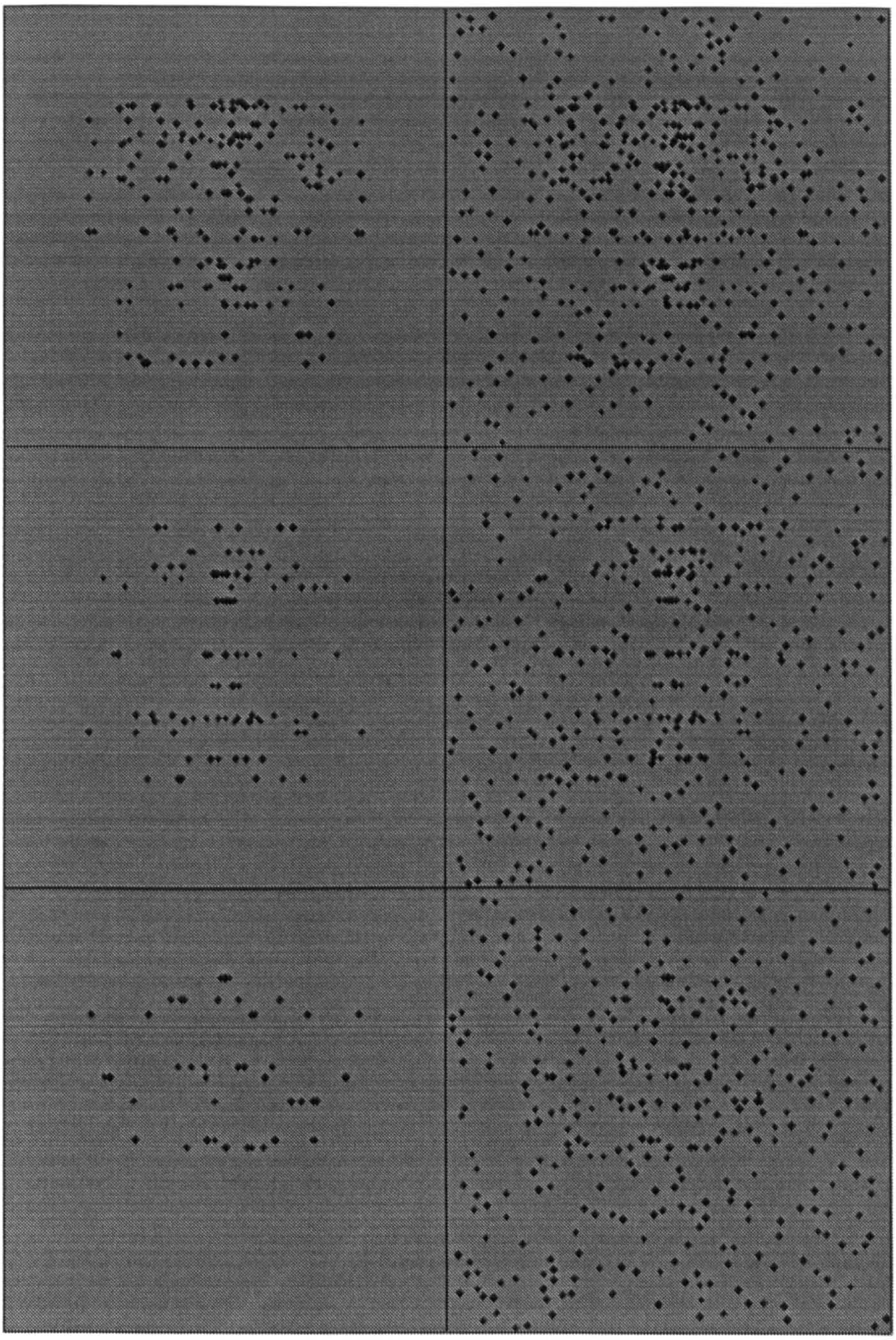


Figure 7.7b. An example of the random dot strings pattern used in Experiment 13. String length of 6 is shown here. This figure is identical in nature to Figure 7.7a, except that within each symmetrically placed dot pair there are four randomly positioned additional elements.

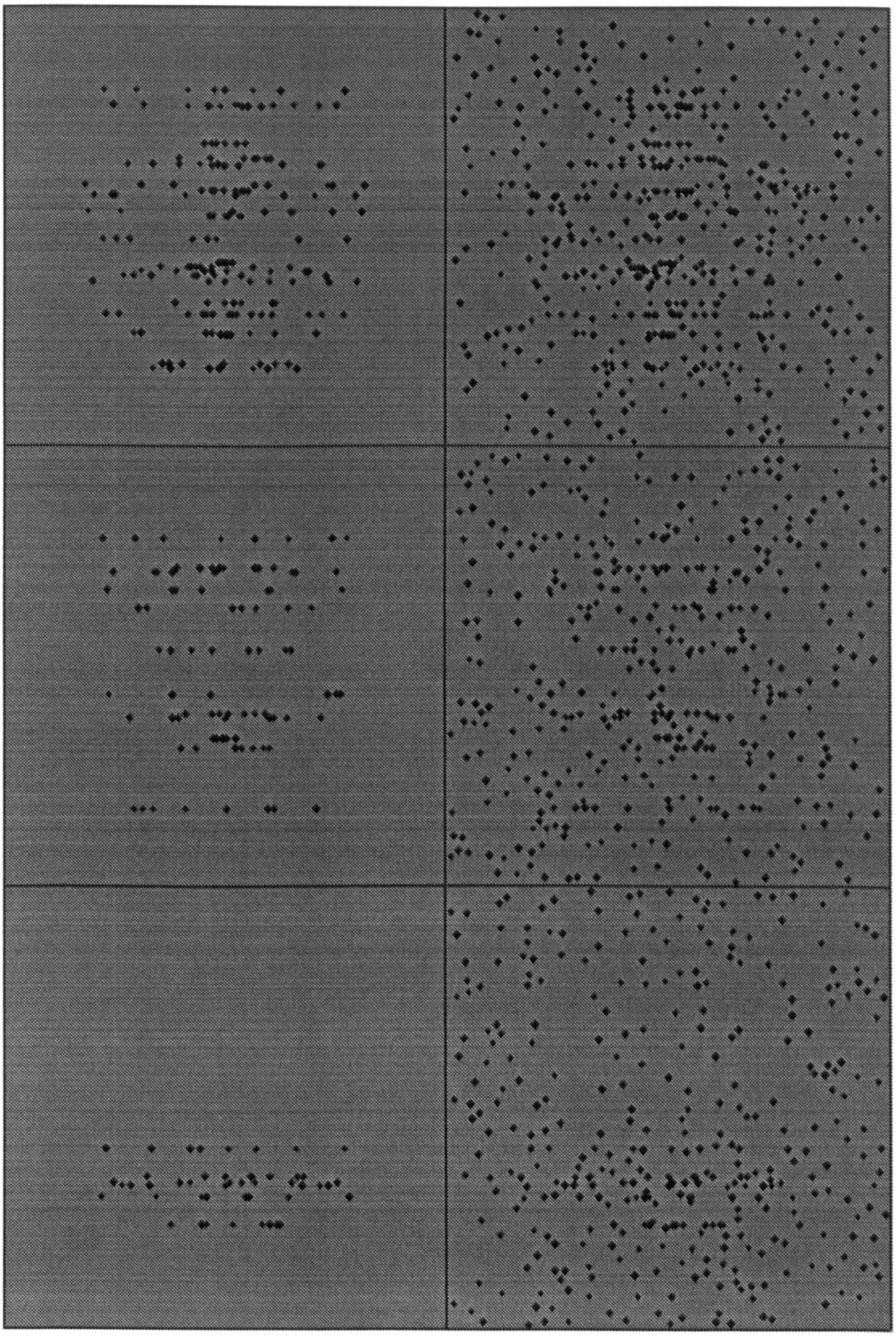


Figure 7.7c. An example of the random dot strings pattern used in Experiment 13. String length of 8 is shown here. This figure is identical in nature to Figure 7.7a, except that within each symmetrically placed dot pair there are six randomly positioned additional elements.

7.5.3 Results

The data from are summarised in Figure 7.8., which shows the threshold number of strings as a function of string length for three subjects. The given threshold measurements represent the number of strings required to detect the target stimuli at the 83% correct point. As there were 200 signal elements in this experiment, full signal is reached at 100, 50, 33, and 25 strings for lengths of 2, 4, 6, and 8 respectively.

The patterns of performance in the detection thresholds show that there is a clear overall improvement in detection performance as string length is increased. In the known axis condition, the thresholds decrease from between 50-80 dot pairs, to only 2-4 strings of 8 elements, whilst in the unknown condition performance improves from 68-88 dot pairs to only 4-6 strings, for 2 and 8 elements respectively. In general, performance improves most rapidly with the initial increase in string length from 2 to 4 elements, levelling out at 6 to 8 elements.

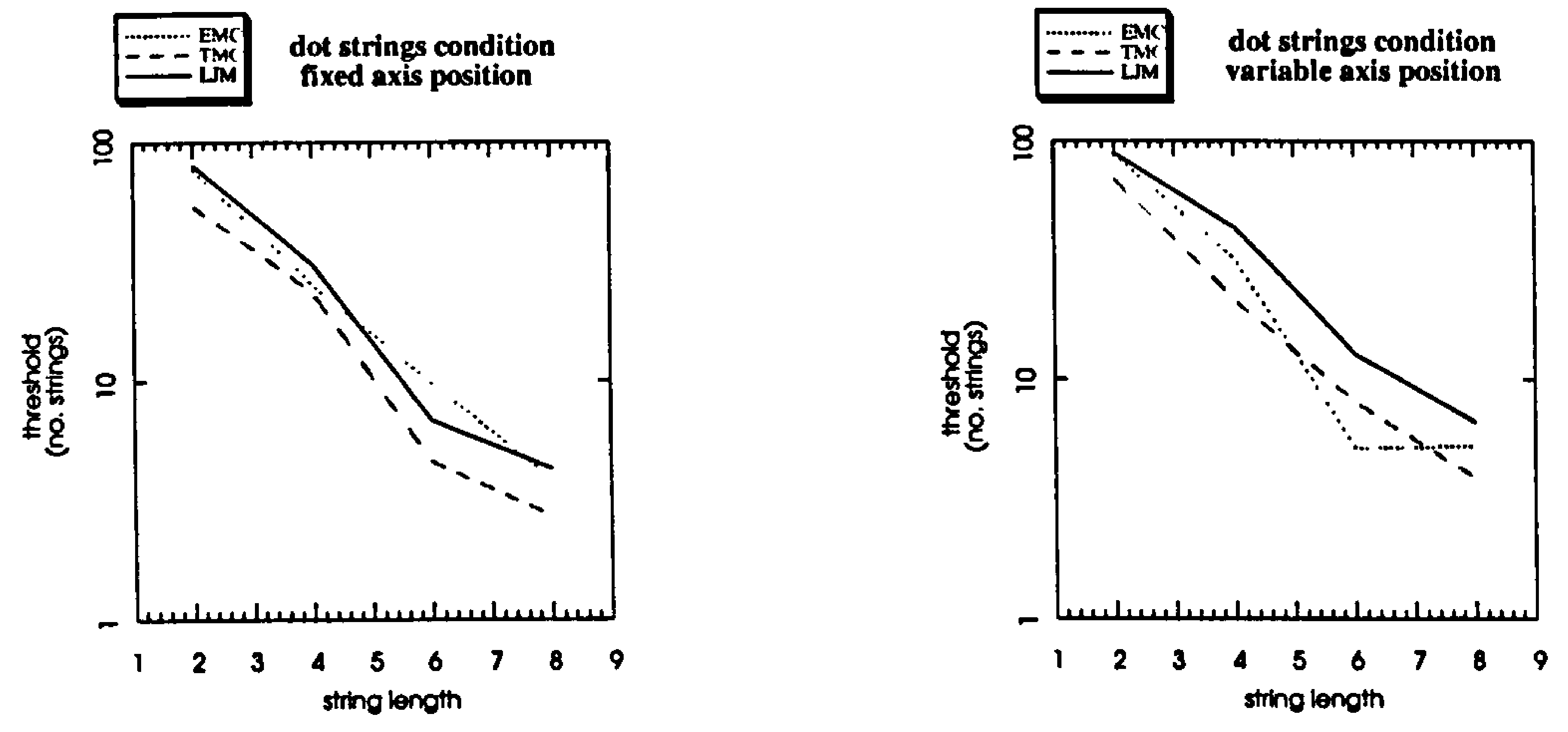


Figure 7.8. Graph to show detection thresholds as a function of string length for 3 subjects. The ordinate is the number of strings required for detection at 83% correct level. Abscissa is the number of elements contained in the disc string. Each data point is the threshold from a single psychometric function, obtained by combining the data from three runs into a single function.

The psychometric functions for each subject at string lengths of 4, 6, and 8, under fixed and variable axis conditions, are presented in Appendix D. At string length 2, the experimental conditions are identical to those in Experiments 2 and 3, the results of which are shown in Figures 4.4 (fixed axis position) and 4.5 (variable axis position). It can be seen that at a string length of 2 elements, the functions are fairly straight, as perfect detection performance is achieved at full signal, but deteriorates immediately that the signal to noise ratio is reduced. However, as string length is increased, the discrimination functions take on the characteristic plateau of perfect detection performance across the middle and upper regions of the stimulus range, followed by a slope toward zero stimulus.

Data from the fixed and variable axis conditions were compared for each string length. Detection performance was significantly better in the fixed axis condition at string length 2 (EMC, $p < 0.02$; LJM, $p < 0.007$; TMC, $p < 0.008$). Note that this condition is identical to that in Experiments 2 and 3. However, the advantage for axis knowledge diminishes at string lengths 4, 6, and 8, and no significant differences between fixed and variable axes are found at these longer string lengths. It should be noted however that as string length increases, the elements in this condition tend to become concentrated around the axis region, due to the fact that there are fewer strings, and a higher concentration of dots within each string. This density effect may provide a density cue to the position of the target in the variable axis condition, which would reduce the effect of axis uncertainty.

7.5.4 Discussion

The data from this experiment reveals that the facilitating effect of increasing string length, found in disc patterns, is also found in dot patterns. Subjects require fewer strings to achieve threshold performance as the number of elements per string is increased. As was found in Experiments 3 and 4, axis position knowledge aids detection at string length of 2, indicating an additional, axis dependent strategy (such as point matching about the axis) is available to the subjects. However, this advantage disappears at the longer string lengths, indicating that subjects are using a more global strategy. The switch to a global strategy would be expected for two reasons. First, because dot strings are more easily detected at a global level than dot pairs, and second because the elements in the middle of the string (i.e., closest to the axis) are not symmetrically placed about the axis, and this should be disruptive to an axis dependent matching strategy. Strong parallel structure clearly aids detection in this task.

7.6 Experiment 14 - Perception of structure in repeated patterns.

7.6.1 Introduction

In Experiment 10 it was established that the visual system is able to detect symmetry at a global level, particularly when the emergent parallel structure is enhanced by additional pattern elements. The stimulus patterns in Experiment 10 had no local symmetric structure about the axis due to the fact that the additional elements were positioned at random points in between the outer symmetric elements. The strings stimuli can not therefore be considered to be perfectly symmetric, and the conclusion drawn from the experiment was that global structure was not perceived in the symmetry relations between individual point pairs, but in the emergent, global, parallel relations amongst pairs or strings of elements. It was further concluded that the visual system is able to detect global structure in 'approximate symmetries'. Precisely what sorts of structure can be included within the bounds of this loose definition is not known, and it is not the intention in this thesis to determine any such bounds. However the two coarse features of the parallel structures identified in the strings stimuli were the elongation of the correlated features and the alignment of these about a midline axis. Elongating the features was found to improve the detection of structure, as shown by the facilitating effects of increasing string length. The aim of this experiment was to investigate whether groups of non-aligned, elongated features can be included in the definition of 'approximate symmetry'. In order to do this, an experiment similar to Experiment 10 was conducted, the difference being that the outer elements of each string were not symmetrically positioned, therefore the strings of elements were not aligned about a midline axis. Instead, the skeleton structure of the stimulus pattern was that of repetition symmetry. As stated, the intention of this experiment was not to measure the level of tolerance to distortions of perfect symmetry, but simply to determine whether structure could be perceived under certain types of distortion. Given this, the advantage of using a repeated pattern was that the horizontal spread of midline points was limited to half the width of the stimulus display (the distance of translation), thereby ensuring that a relatively cohesive pattern was produced.

It should be noted that the strings in this experiment are all of equal length in the sense that the outer elements are separated by the same physical distance. This may produce a certain uniformity in the patterns, as the density of elements in each string (as determined by number of elements and distance of separation) will be constant, due to the constant distance of translation. However, it is expected that this will be imperceptible in the stimuli due to the fact that the elements are randomly positioned along the string and are likely to occlude one another, particularly at the higher numbers of elements per string.

It is necessary to clarify some of the terms used to describe the stimuli. Up to this point, the term ‘string length’ has been used to refer to the number of pattern elements in each string, regardless of the absolute length of the string. ‘String length’ is used in the same manner in this experiment although in absolute terms the strings in these stimuli are of the same length.

7.6.2 Method

Stimuli

The stimuli were similar to those in Experiment 10, with the exception that the target structure was repetition symmetry rather than bilateral symmetry. The repeated structure was generated by laying a random distribution of disc elements on one side of the midline and then translating each element by a standard distance of one half of the stimulus width (100 pixels, 0.72 degrees).

Four string lengths were used in the experiment. Common to all of these was an outer pair of discs which were separated by a constant distance. The outer pairs with no additional elements was taken to be a string of two elements. Strings of 4, 6, and 8 elements were generated by placing 2, 4, and 6 elements respectively along the virtual line between the outer pair.

As in Experiment 10, the distractor stimuli used in the experiment also contained strings. These were generated between randomly positioned discs of constant separation, in order to create strings with random position and orientation with respect to the axis. The noise targets thereby contained strings which were equal in number and length to those in the structured targets but which were not aligned. Sample stimuli are shown in Figure 7.9.

Subjects

The subjects in this experiment were TMC, JAJ, and FC (see General Methods for subjects' details).

Task

The subject's task was to discriminate the target stimulus containing the repetition symmetry from the distractor stimulus containing the non-orthogonal strings. Subjects were shown a number of sample stimuli to explain the task, which made clear the nature of the strings, the nature of the repeated structure, and the orientation and range of positions of the target stimuli within the background window.

Subjects were tested on four string lengths of 2, 4, 6, & 8 elements. The four string lengths were randomly interleaved in a single run of 256 trials. The trials were blocked by axis condition.

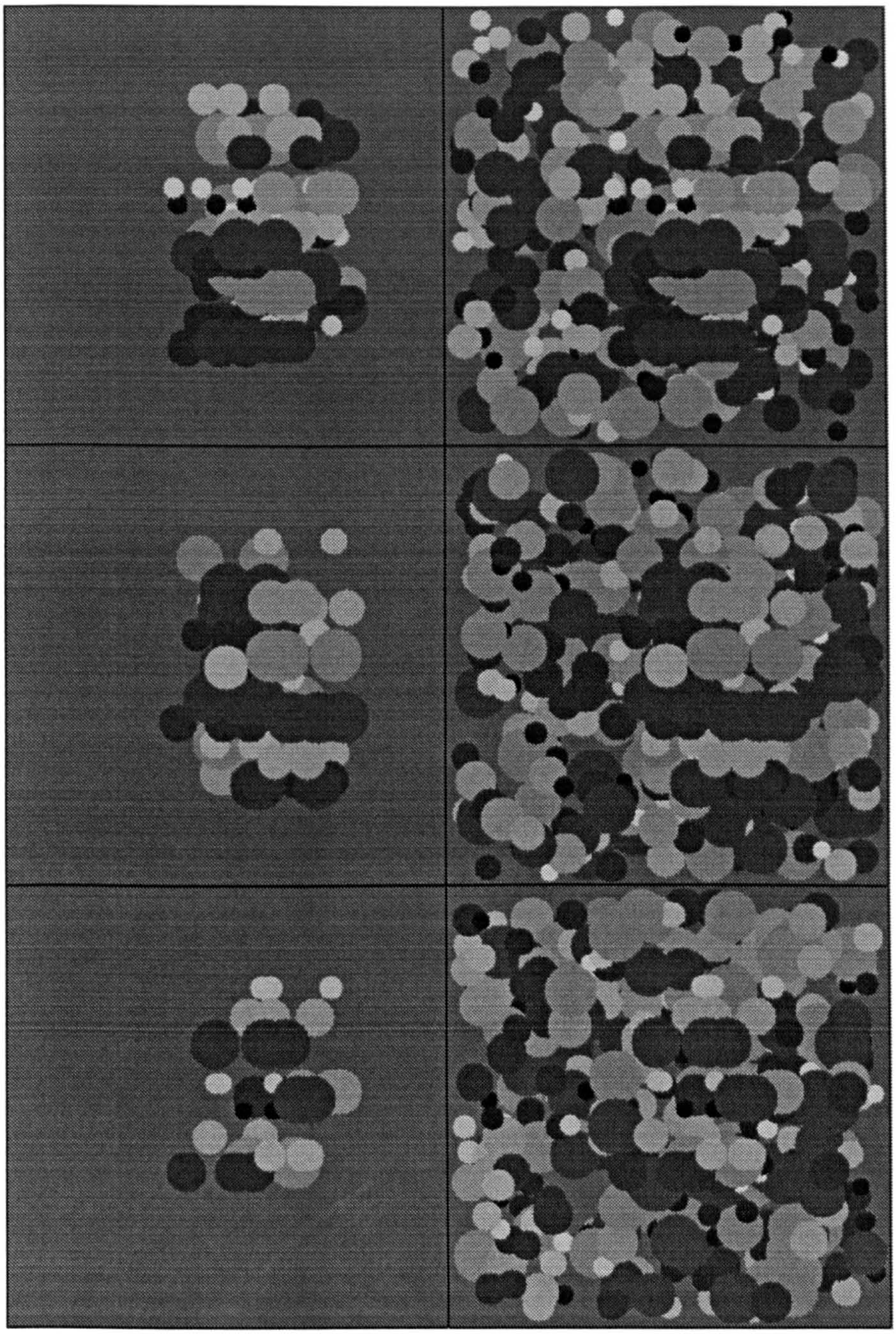


Figure 7.9a. An example of the disc strings pattern used in Experiment 14 (repeated structure). String length of 4 is shown here. The rows show the stimulus at 100% (top row), 50% (middle row) and 25% (bottom row). In the left hand column the symmetric targets are shown without a noise background. In the right hand column, the stimuli are as presented to the subjects. It can be seen that within each translated disc pair there are two randomly positioned additional elements, which sometimes occlude one another. It can be seen that disc size and grey level are matched within pairs, but vary between pairs. In the random axis condition the position of the stimulus window was varied within the outer background window.

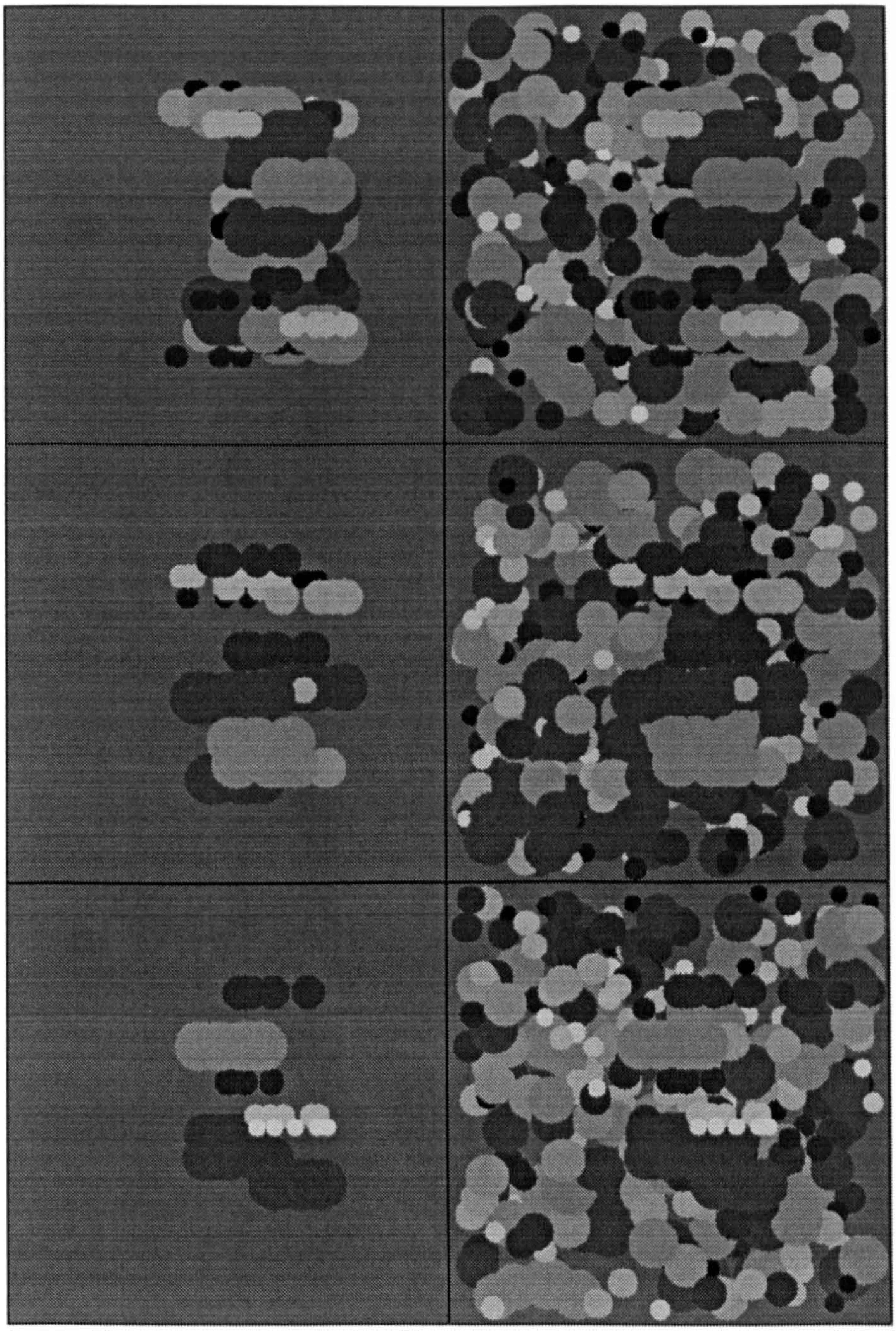


Figure 7.9b. String length of 6 is shown here. This figure is identical in nature to Figure 7.9a, except that within each translated disc pair there are four randomly positioned additional elements.

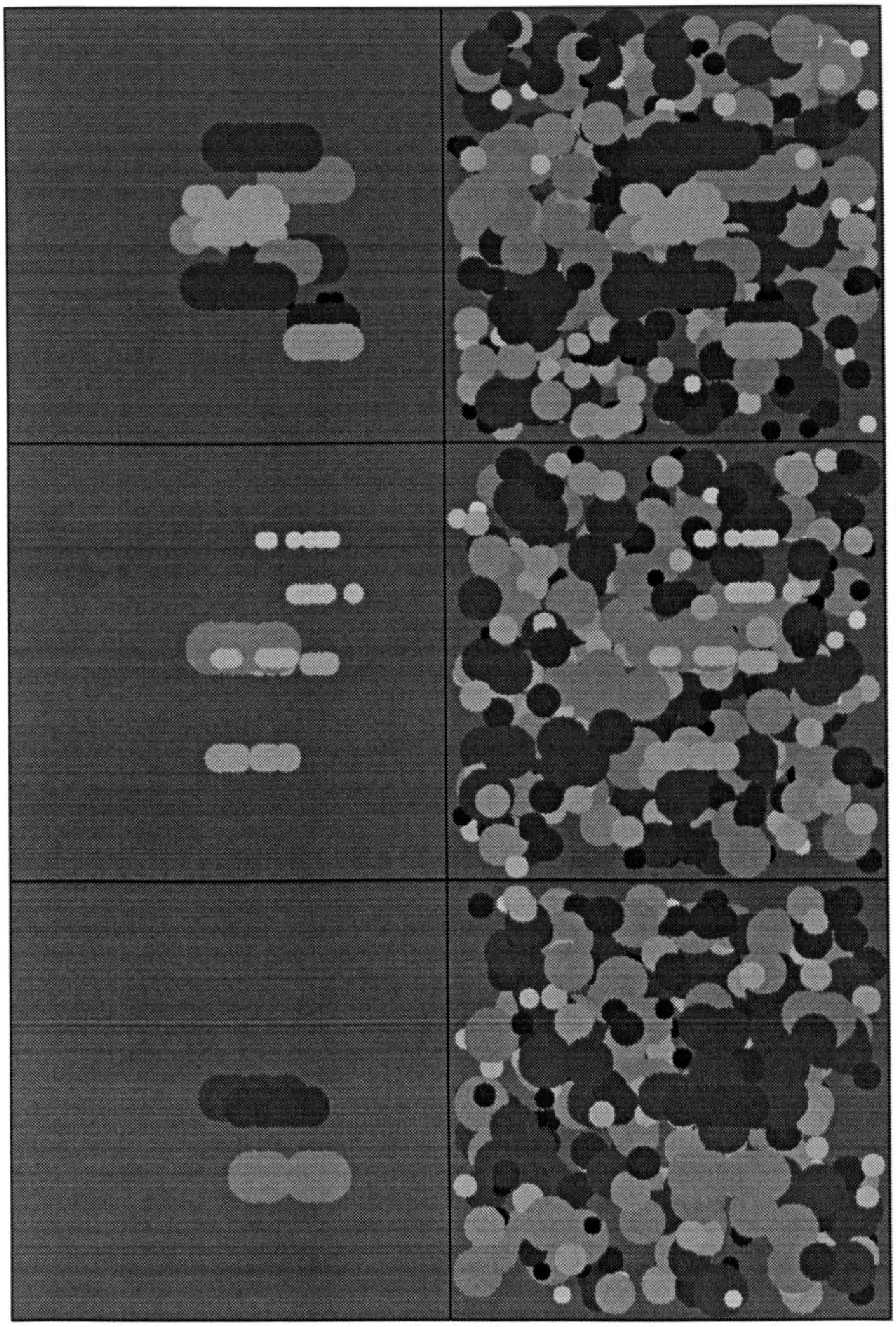


Figure 7.9c. String length of 8 is shown here. This figure is identical in nature to Figure 7.9a, except that within each translated disc pair there are six randomly positioned additional elements.

7.6.3 Results

The data are summarised in Figure 7.10., which shows the threshold number of strings as a function of string length for three subjects. The given threshold measurements represent the number of strings required to detect the target stimuli at the 83% correct point. Where subjects fail to obtain a detection threshold, the data point is arbitrarily set to 100.

The patterns of performance in the detection thresholds shown in Figure 7.10 reveal that there is an overall improvement in detection performance in both the known and unknown axis conditions as string length is increased from 2 to 8 elements per string. In the known axis condition, only one subject achieves threshold performance at a string length of 2 elements, however, performance improves greatly as the number of elements per string is increased, such that at strings of 8 elements, only 2-5 strings are required for detection. Similar patterns of performance are found in the unknown axis condition in which again, two subjects fail to detect the repeated targets of two strings, but are able to detect only 2-5 strings of 8 elements.

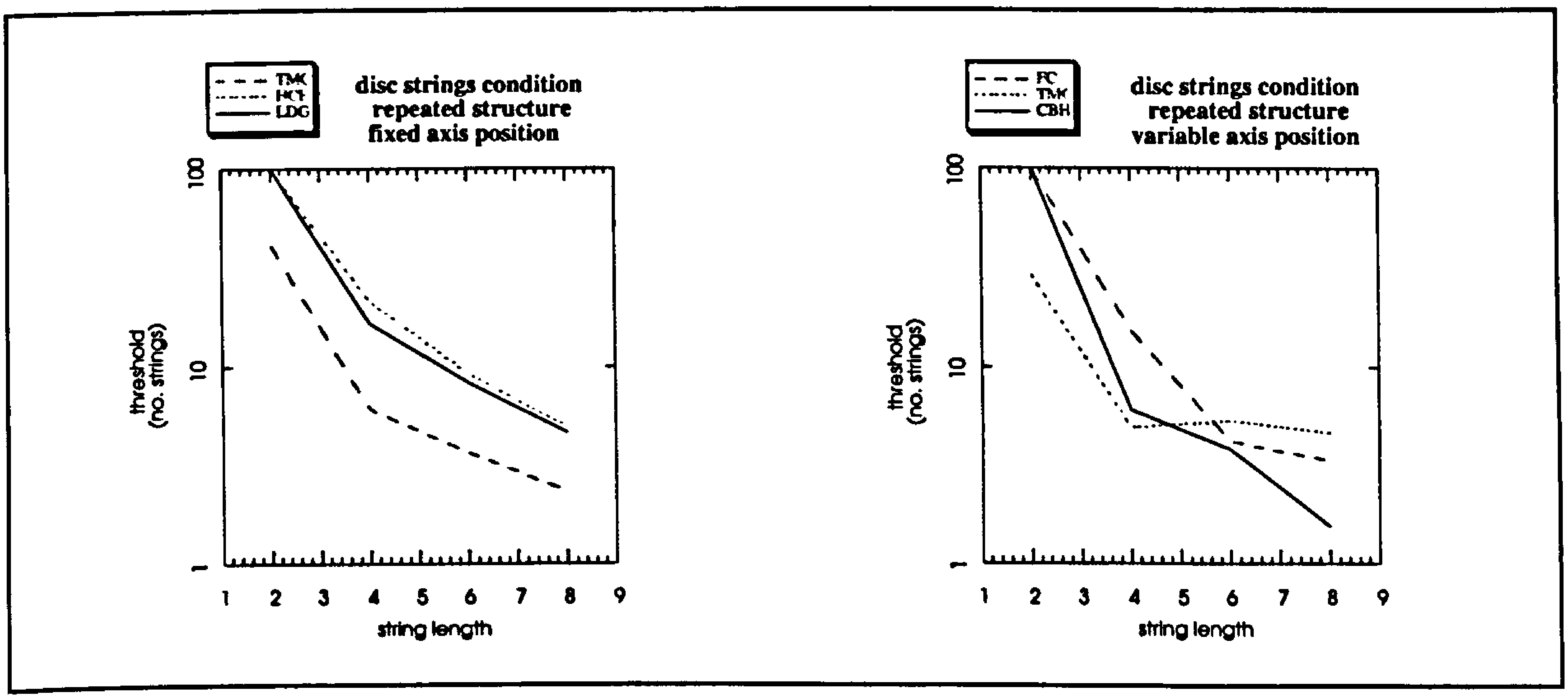


Figure 7.10. Graph to show detection thresholds as a function of string length for 3 subjects. The ordinate is the number of strings required for detection at 83% correct level. Abscissa is the number of elements contained in the disc string. Each data point is the threshold from a single psychometric function, obtained by combining the data from three runs into a single function.

The psychometric functions are presented in Appendix E. It can be seen that the shape of the psychometric functions is similar across axis condition. At the string length of 2 elements performance is either at chance, or is highly variable across the stimulus range. However, at string lengths of 4 to 8 elements the functions begin to show the characteristic shape of a gradual increase as the stimulus level is increased, becoming shallow or flat at high stimulus levels.

Only one subject completed both central and random axis conditions on this experiment, and a comparison between the psychometric functions from these two conditions found no significant differences between the two, indicating that prior knowledge of axis condition does not aid detection of the targets.

7.6.4 Discussion

The results of this experiment are interesting in light of previous findings that repetition symmetry is more difficult to detect than bilateral symmetry in random dot patterns. This finding is replicated here with pairs of disc elements in both known and unknown axis conditions, and the effect is considerable, as two subjects are unable to detect the targets of two elements. However this disadvantage is not found at string lengths greater than 2 elements, and although the thresholds are generally higher at all string lengths than those in the symmetric patterns of Experiment 11, the same overall effect of improving performance is observed at the string lengths 4 to 8.

One possible reason for the difference between detection of symmetric and repeated pairs of discs is that in the repeated patterns, the elements are separated by a sufficiently large distance that the pairs are not perceived as elongated structures, therefore the targets do not have the striated appearance (found in the symmetric targets), which was thought to aid global detection. Global detection is possible however, when the parallel structure is enhanced, and his suggests that the presence or absence of emergent parallel structure in the stimuli determines detection performance, rather than the precise transformational relationship between the elements.

The general conclusion from this experiment is that detection of global structure is only slightly disrupted when the midpoint collinearity between the strings is disrupted. Some caution is required in generalising this finding, as the distribution of midline points was rather limited in the present experiment, and some effect on detection performance would certainly be expected as a result of increasing the distribution of midpoints beyond this (Jenkins 1983b).

However, the main point of interest is that the visual system is indeed able to detect what has so far been described as 'approximate symmetry'. Whilst the results of this experiment do not support a quantitative interpretation of this term, the qualitative properties of 'approximate symmetry' may now be more fully described. Coherent structure can be perceived in a relatively compact set of elongated features. There are a number of patterns which can be described in mathematical terms, such as repetition and reflection, which contain both properties of coherence and elongation, given certain stimulus conditions which allow some degree of fusing of correlated features. Bilateral symmetry has been intensively studied as a particularly salient pattern type, the implicit assumption of this interest being that symmetric structure is a special status pattern. However, the results of this experiment suggest that symmetry may be a conveniently described, (and particularly salient) example of a much larger set of patterns which contain to some degree, the properties of elongation and coherence, all of which are treated by the visual system in much the same way.

The results of this experiment further suggest that the property of elongation may, in itself be sufficient to signal the presence of an 'object' or a foreground feature. In Experiment 10, and the present experiment, target detection was found to be possible in the presence of as few as 2-3 strings of elements, however it is important to note that this level of performance was obtained under conditions of fixed, vertical target orientation, therefore the subjects are likely to be relying to some extent on orientation cues to do the task. The effect of orientational uncertainty on detection of the strings stimuli is investigated in Experiment 15

7.7 Experiment 15 - The effect of orientational uncertainty on detection of strings.

7.7.1 Introduction

The purpose of this experiment is to investigate the effect of orientational uncertainty on detection of the string stimuli. The absence of an effect of axis knowledge in the strings stimuli has been taken to indicate global detection of the stimuli. However, the targets in all conditions had a fixed vertical axis orientation, therefore the discrimination task could feasibly be done by detecting horizontal, rather than parallel, structure. Even under conditions of axis positional uncertainty, the stimuli used in the detection tasks are more heavily constrained than natural stimuli and objects in naturalistic settings, for which no high-level knowledge of the visual scene can be assumed, prior to segmentation. The purpose of this experiment is to investigate detection of the strings stimuli under conditions of unknown axis orientation, in order to establish whether these targets are detectable under the most difficult presegmental conditions of unknown position and orientation. Without prior knowledge of pattern orientation, the only way to determine whether any single string is meaningful is to detect other proximal, parallel strings. It is predicted that under conditions of orientational uncertainty, detection will depend crucially on the presence of strong, parallel structure.

7.7.2 Method

Stimuli

The stimuli were identical to those in Experiment 10 except that the orientation of the target axis was varied randomly from trial to trial between 0 and 180 degrees. Performance was measured under both central and random axis conditions.

Subjects

The subjects in this experiment were CBH, LAW, LJM, LDG, and TMC (see General Methods for subjects' details).

Task

The subject's task was to discriminate the target stimulus containing the parallel strings from the distractor stimulus containing the non-parallel strings. Subjects were shown a number of sample stimuli to explain the task, which made clear the nature of the strings, the variation in disc sizes, the range of positions orientations of the target stimuli within the background window.

Subjects were tested on four string lengths of 2, 4, 6, & 8 elements. The four string lengths were randomly interleaved in a single run of 256 trials. The trials were blocked by axis condition.

7.7.3 Results

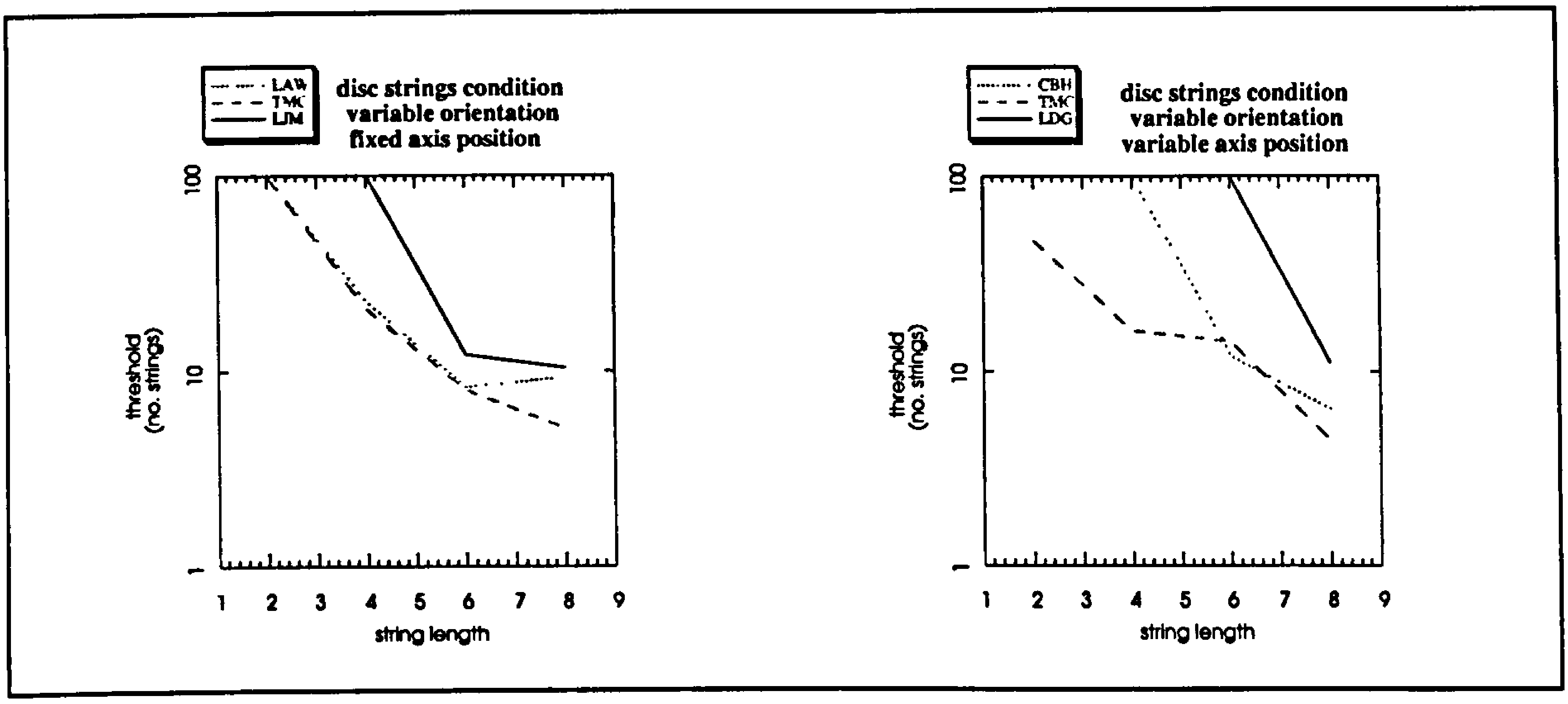


Figure 7.11. Graph to show detection thresholds as a function of string length for 3 subjects. The ordinate is the number of strings required for detection at 83% correct level. Abscissa is the number of elements contained in the disc string. Each data point is the threshold from a single psychometric function, obtained by combining the data from three runs into a single function.

The data are summarised in Figure 7.11, which shows the threshold number of strings as a function of string length for three subjects. The given threshold measurements represent the number of strings required to detect the target stimuli at the 83% correct point. Where no threshold was obtained, the data point is set arbitrarily to 100 to indicate that the subject failed to perform at threshold level in that condition.

The patterns of performance in the detection thresholds show that subjects have difficulty in detecting the targets at the shorter string lengths. Only one subject in the fixed and one in the variable axis condition achieved threshold performance at string length 2. As length increases to 4 and 6 elements the subjects begin to be able to detect the targets, such that at 8 elements per string all subjects are able to detect targets comprised of around 12 strings.

The psychometric functions are presented in Appendix F. It can be seen that initially, at the shorter string lengths, the psychometric functions are level at chance performance. However, as string length increases, the functions begin to slope upward, although subjects do not achieve perfect detection performance, even at the highest stimulus levels in this condition. Randomising the axis orientation causes a disruption in performance across the stimulus range, however, the degree of disruption is reduced as string length is increased.

7.7.4 Discussion

The results of this experiment indicate that stimulus targets of unknown orientation can be detected under conditions in which the elongation in the structure is sufficiently strong and there is some degree of parallel structure in the stimuli. As expected, target detection was not possible in this condition given 2 or 3 strings, and subjects ability to detect the presence of fewer strings in the fixed orientation experiments, such as Experiment 10 does suggest that knowledge of absolute orientation provides a cue to the target stimuli at the lowest stimulus levels. Nonetheless, targets with strong parallel structure are detectable under conditions of unknown orientation in both the fixed and variable axis conditions.

This experiment supports the proposal that elongated and parallel structure can be detected in the absence of any prior knowledge of target position or orientation. This finding supports the broad proposal made in this thesis that grouping heuristics based upon the detection of approximate symmetry may provide a method for image segmentation which is low-level, flexible, and sensitive to generalised properties of objects.

7.8 General discussion

The results of this series of experiments show that strengthening the orthogonal structure in symmetric patterns aids detection of structure. Strings of elements are more easily detected than pairs. This effect is strongest in the case where all of the pattern elements in a string are identical in size and luminance. The presence of strong orthogonal structure, due to the presence of strings, serves to reduce effects of variability within the pattern and also the effects of positional and orientational uncertainty. The result from the dot strings experiment (Experiment 13) cannot be directly compared with the disc strings as the threshold measurements do not correspond to the same number of elements in the two stimulus types. However, increasing string length has a qualitatively similar effect in dots as in discs: performance improved with increasing string length. Some caution is needed in interpreting any effects of axis knowledge in the dot strings condition because the location of the target is visible to the subjects due to local density cues.

Equivalent performance under both known and unknown axis position suggests that the targets comprised of element strings can be detected globally, and without explicit testing of elements in the axis region. Further evidence for the use of a global detection strategy comes from the finding that varying the grey level of correlated elements completely disrupts detection of the targets (Experiment 13). This result suggests that the strings are perceived as whole structures rather than composite structures, and that contrast is the element characteristic that binds the strings. Compared to the effect of contrast, other element characteristics are relatively unimportant. Variation in the size of the correlated pattern elements (Experiment 11) was found to disrupt detection performance, but less so than in the variable contrast condition. The effect of varying disc size was also found to be compensated by strengthening the orthogonal structure. Thus, unlike contrast variation, size variation does not prevent global detection of the parallel structure. The advantage for symmetry over repetition (i.e., the effect of disrupting the perfect midpoint collinearity of symmetry) was also found to be reduced by increasing string length (Experiment 14). The detection of global structure does not therefore require correlated elements to be perfectly matched, or perfectly aligned about a single midpoint but can be performed on the basis of approximate parallel structure. Experiment 15 showed that orientational uncertainty does disrupt detection performance, but that targets with sufficiently strong parallel structure are detectable, even where both the orientation and position are unknown to the observer. It is interesting that orientational uncertainty (even under a known axis position) is more detrimental to performance than positional uncertainty. Given that a global strategy is used under both conditions, as the axis is unknown to the subject, the particularly disruptive effect of orientational uncertainty may suggest that a normal horizontal and vertical reference frame may be used in the global detection of structure. However, this is only a tentative suggestion. The intention in including the orientation condition was to look at the effect of uncertainty rather than specific effects of orientation and the data is insufficient to allow any firm conclusions about orientational effects to be drawn, (for example the existence of a stable reference frame would be supported by data which showed that subjects performance was poorer in a fixed non-vertical orientation than in a fixed vertical orientation). Thus, it is possible to say from this data that although orthogonal structure can be detected under orientational uncertainty, there is some advantage for fixed axes, even under positional uncertainty. Further experimentation is required to determine whether this is a vertical advantage.

8

THE VISUAL PROCESSING OF SYMMETRY

8.1 Summary of results

8.1.1 Symmetry detection in basic random dot stimuli (Experiments 1-3)

In Chapter 4, experiments were reported from which it can be concluded that the high levels of performance in symmetry detection previously reported, depends generally on subjects having good information about the location of the axis of symmetry. When this information is denied to subjects, their performance deteriorates considerably. At lower levels of symmetric dots, being able to see the outline of the target was of some small additional benefit. Given that the main focus of the research in this thesis is about the possible role of symmetry in segmentation, it is the data obtained under unknown axis conditions that will now be discussed.

Thus, in Experiment 3, in order for subjects to correctly identify the symmetric target without prior knowledge of the axis, the number of dot pairs had to be greater than 68%. In order to reach 100% correct, it was necessary for 80-100% of the dots to be symmetric.

8.1.2 Symmetry detection under conditions of constant signal density (Experiments 4-6)

In Chapter 5, experiments were reported in which the conditions for detection were further investigated. It can be concluded from these experiments that symmetry can be detected in random dot targets under conditions of no noise dilution, given a sufficient density of uniform contrast symmetric pairs. In the unknown axis condition, where there was no noise dilution of the target, subjects were able to detect symmetry at 83% correct, given 17-29% signal. In order to reach 100 % correct it was necessary for 20-50% of the dots to be symmetric.

With noise dilution added to the symmetric targets, a greater number of dot pairs were required to detect the symmetry. The proportion of dot pairs had to be greater than 50-60% to reach 83% correct and in order to reach 100% correct over 70% signal was required.

Where the symmetric targets were of mixed contrast pairs, the number of pairs required to detect the symmetry at 83% correct increased to 55-80, and 70-100 pairs were required to reach 100% correct performance.

It was concluded from this series of experiments that the location of the symmetric target in random dot stimuli was dependent on the presence of symmetrically positioned dot clusters and therefore that some kind of local grouping must precede symmetry detection. Two conditions were found to be necessary for local grouping to occur: firstly the distribution of elements should be nonuniform and secondly, within each local cluster the elements should be uniform in contrast.

8.1.3 Symmetry detection in disc patterns (Experiments 7-9)

In Chapter 6, symmetry detection was measured using a novel type of random stimulus which incorporated the conditions of high density, low noise dilution and uniform contrast, identified in Chapter 5. In these stimuli, the pattern elements were large, and variable in size and contrast, such that both members of each pair had the same size and grey level and thus could be identified with each other. Although they were presented against a noise background, the pattern elements were not occluded by noise.

A baseline measure of detection performance (in the unknown axis condition) found that 38% and 48% signal (19-24 pairs)was required to detect symmetry at 83% correct. When the size of the discs were varied within pairs, detection performance was slightly disrupted and 74%-92% signal (37 and 46 pairs) was required to reach 83% correct performance. However when the grey level of the discs was varied between pairs subjects were unable to detect symmetry at the 83% correct level, therefore no threshold measure of performance was obtained for this condition.

It was concluded from these experiments that the detection of symmetric structure depends on the global correlation of symmetrically positioned regions of equal luminance. Some variation in the respective sizes of these regions is tolerated. A further proposal on the basis of these results was that the major structural cue in these stimuli may not be the presence of symmetric point pairings, but rather the presence of a global parallel structure which emerges from the pairing of extended regions of equal luminance.

8.1.4 Detection of parallel structure (Experiments 10-15)

In Chapter 7, experiments were reported in which the salience of parallel, rather than symmetric structure was examined. The stimuli comprised strings of elements, which were generated by distributing additional elements along the virtual line joining each disc pair.

It was established that increasing the number of elements in a string greatly improved detection performance. The number of strings required to detect structure at the 83% correct point was reduced from 19-24 strings of two elements to only 2-3 strings of 8 elements. Enhancing the parallel structure in the stimuli resulted in a marked improvement in detection performance.

The effect of varying the relative size of symmetrically positioned elements found in Chapter 6 was also found in the string stimuli at the shorter string lengths. Performance was found to be slightly, but not significantly disrupted at string lengths of 2 and 4 elements, however at the longer string lengths of 6 and 8 elements the effect of varying element size was negligible, suggesting that where the global parallel structure in the stimuli is sufficiently strong, local variation in the size of the pattern elements has little perceptual effect. Varying the grey level of elements within a string was found to severely disrupt detection performance at all string lengths, even given prior knowledge of the axis position. Detection of parallel structure in these stimuli was therefore found to be heavily dependent on the presence of extended regions of equal luminance as predicted by the results of the experiments in Chapter 5.

The above experiments indicate that the detection of global symmetric structure does not require perfect symmetry at a local level. Some variation in the size and relative positioning of the local pattern elements is tolerated. In Experiment 14 it was further established that structure was detectable in patterns where the symmetric structure was disrupted at a global level. Where the striated appearance of the patterns was sufficiently strong, perfect alignment of the features about a single axis was not necessary for the detection of coherent structure in the stimuli.

Finally, it was shown that where the parallel structure was sufficiently dense, it was detectable given no prior knowledge of axis position or orientation (Experiment 15). It was concluded that elongated regions of consistent (but not necessarily constant) contrast, approximately aligned about an axis were useful cues to the presence of structure in a pattern.

8.2. General discussion of results

It is necessary to provide some clarification of the terms used in the following sections to describe the different components of patterns. The term 'pattern' is used to refer to the global organisation in the image. 'Element' is used to refer to individual pattern elements which are not grouped in any way. 'Feature' and 'structure' are used to refer to combinations of elements which have been grouped by the visual system to form structured components of patterns.

8.2.1 Symmetry and segmentation

In order for pattern structure to be presegmental, it should be detectable, given no prior knowledge of location, size, or orientation. By measuring detection performance under both known and unknown axis conditions, it was possible to gauge the extent to which subjects performance was dependent on prior knowledge of these pattern details. In all conditions therefore the performance measure of most interest was the difference in subjects performance between the known and unknown axis conditions. Under this set of criteria, symmetry in random dot patterns was found to fare poorly as a readily segmentable structure.

8.2.2 Symmetry detection in dot patterns

Symmetry can be characterised by the presence of elements which are aligned at equal distances on opposite sides of a midline axis. The task facing the visual system is to identify which dots are paired in this manner and are thus significant or meaningful as a group. In principle, this requires that grouping be performed in two directions. An initial stage of grouping must be carried out to identify which dot is symmetrically paired with which (i.e., to group elements into pairs). A second grouping is then required to draw the symmetrically positioned pairs into a global symmetric pattern. Because all of the pattern elements are identical in random dot stimuli, any two points on the image form a potential pair, and the meaningfulness assigned to any single pair will therefore be zero. The selection of a symmetry axis must therefore be dependent on the perception of the common relationship between a number of dot pairs, that is, alignment about the same axis.

In Experiments 1, 2, & 3, the density of the signal dots decreased as the stimulus level decreased, and subjects were unable to detect the presence of point pairs at the lower stimulus levels, even under conditions of fixed axis position and orientation, which provided both a known axis and a dimension along which to match. However, near perfect symmetry detection was possible at the high stimulus levels.

The effect of target dot density was investigated in the following set of experiments (4-6) in which it was found that detection was possible across a wider range of stimulus levels, given a high and constant target density. It was concluded that local grouping, and the emergence of distinctive large scale symmetric structure made possible the detection of symmetry in random dot patterns. This result supports the conjecture that whilst a single point pair carries very low inherent meaning and is highly susceptible to noise, multiple correlations along the same dimension are more meaningful and are somewhat resistant to noise. As a consequence of this finding, the operational definition of visual symmetry was modified to take account of the relationship between, as well as within, point pairs. The importance and role of the inter-pair relationships was confirmed in Experiments 4-6, in which it was established that subjects are able to detect the symmetric positioning of emergent features which arise by chance from the local clustering of point pairs in random dot patterns. These emergent features are distinctive in two ways. They are irregularly shaped and sized, and they are of lower mean luminance than the background, due to the locally higher density of elements. In Experiment 5 it was found that the salience of these local clusters was reduced by adding noise to the symmetric pattern. The reduction in detectability in this condition may have been due to two causes: first the shapes of the emergent features were merged into the noise and second the local contrast differences (which are caused by the presence of local signal densities) were reduced, as the additional noise increased the background density to the same level as the signal density.

Experiment 6 investigated the role of local contrast in symmetry detection, finding that local grouping prior to symmetry detection is heavily dependent upon the presence of coherent regions of uniform contrast which are differentiated by contrast from the background.

Experiments 1 - 6 specified some of the stimulus conditions which allow the grouping of local elements. Local grouping was found to be prerequisite to the detection of symmetry in dot patterns and involves the clustering together on each side of the axis, groups of elements of similar contrast, which are matched to identical groups at a common orientation. Local grouping aids symmetry detection by reducing the number of potential matches in the image, and creating a number of additional stimulus dimensions by which to match, such as element shape, size and contrast.

8.2.3 Symmetry detection in disc patterns

A further series of experiments was carried out in order to determine which stimulus attributes are most useful in the detection of global symmetric structure. In the stimulus patterns containing pairs of symmetric discs, the elements were uniquely paired on the dimensions of grey level, size and position, thereby creating characteristic local structures. In comparison with the dot stimuli, in which the elements were paired only on the single dimension of position, there was relatively little difference in detection performance in the known and unknown axis conditions, suggesting that local structures are more useful in symmetry detection than local elements. By selectively disrupting the paired attributes of size and grey level it was established that the local structure is carried mainly by the grey level matches and that the relative size of the discs is a secondary feature of the symmetric structure. This pattern of results suggests that the mechanism which detects symmetry at a global level may be dependent upon local contrast matches across the axis and variation in contrast along the length of the axis. The series of local contrast matches in these stimuli produces a clear parallel structure amongst the pairs of stimulus elements. This parallel structure is not exclusive to bilateral symmetry, but emerges under a much more general set of conditions in which a series of paired elements or elongated structures are approximately aligned in an orthogonal fashion.

8.2.4 Parallel structure and segmentation

The saliency of parallel structure was shown in the final series of experiments reported in Chapter 7. By generating structure using strings of irregularly positioned elements rather than pairs, the perfect symmetric pattern in the targets was disrupted, but the parallel pattern was strengthened. It was established that these non-symmetric patterns containing the two features of elongation and parallelism were readily detectable under the conditions specified for judging pre-segmental detection.

The saliency of non-symmetric parallel pattern suggests that parallelism between local structures may be sufficient for segmentation and that the presence of perfectly symmetrically paired elements is neither sufficient, nor necessary for the detection of coherent pattern. Given that the parallel pattern is most obviously present in the contrast matches across the axis it was expected that detection performance would be severely disrupted if the contrast was varied within each local structure, but less so if the size of the elements was varied. This was found to be the case, and further supports the proposal that global pattern can be detected from local structures of extended contrast, which are differentiated from the background by contrast, and positioned in parallel with respect to one another.

8.3. Consideration of filter responses to symmetry

8.3.1 Filters

It was concluded in Chapter 1 of the thesis that presegmental symmetry detection cannot depend on prior knowledge of pattern position or orientation and must therefore require a general detection mechanism which operates globally and in parallel. It was proposed that spatial filtering operations in early vision may make explicit the emergent structure in symmetry and similar pattern types.

Through the series of experiments, two very simple conditions have been identified which are thought to be sufficient for the presegmental detection of symmetry. First, correlated features should be of equal contrast, and second those structures generated by equal contrast features should be approximately parallel to one another. The global pattern which emerges from these two conditions is that of a series of uniformly oriented, elongated structures. Detection of this pattern does not imply a semantic description of symmetry, or of the image content, but simply that some meaningful organisation has been extracted from the raw visual input. This may occur at a low level in the visual process.

There is strong evidence for a filtering operation in mammalian vision that is selective for spatial scale and orientation. Physiological correlates for mechanisms which are selective to scale and orientation are found in the columnar cortical organisation in which columns of cells are tuned to a particular orientation (Hubel and Wiesel, 1962) and to a range of narrowly tuned spatial frequencies (Enroth-Cugell and Robson, 1966; Hubel and Wiesel, 1977; De Valois, Albrecht and Thorell, 1982). The patterns of performance found in psychophysical studies reflect the functional architecture of the visual cortex. Sensitivity can be selectively fatigued to particular spatial scales and orientations (Campbell and Robson, 1968; Blakemore and Campbell, 1969; Graham and Nachmias, 1971; Wilson and Bergen, 1979).

Neural units have been identified in the visual cortex of monkeys which are optimally stimulated by elongated blobs or bars of a particular length, width and orientation. These are described as simple cells and have a centre/surround architecture which responds maximally to change in contrast across the retinal receptive field of the cell. An important property of these simple cells is therefore that they do not respond to homogeneous stimuli. Simple cells perform the equivalent to a simple, orientation sensitive, filtering operation on the visual stimulus, and it is possible that such an operation may provide an early mechanism for the detection of the elongated structures which emerge in symmetric patterns.

In effect, the filtering operation measures across the image, the extent to which the structure in the image corresponds to the shape of the chosen filter. In 2D images it is necessary to smooth along a continuum of different directions around each point. Filters can be made to be selective for orientation by elongating the smoothing function in one direction so that it will respond maximally to elongated structure at the same orientation.

The result of filtering an image is a representation of the raw image in which large values indicate the presence of structure that is similar to shape of the filter. Thus elongated filters detect elongated, oriented structure in images.

An important parameter of the filter function is spatial scale. The scale of information in the output image is determined by the size of the filter function, and larger size filters detect coarser scale structures than do smaller filters. In any image, fine structure is more dense than coarse structure.

8.3.2 Blobs

The filtering process does not explicitly detect image features. The filtered image is a simplification of the raw image in which the variations in response value are much more constrained. Zero values in filtered images are what is expected as a null response. Departures from zero are significant; the sign of a filter response is the most significant aspect. Thus it is sensible to treat as single primitives, those regions of filtered images where the sign (i.e., the direction of the departure from zero) does not change. These will be called blobs and the general formulation of Watt (1991) will be followed.

The term primitive carries a significant interpretation. It is proposed to use a simple description of each blob, in terms of length, orientation, mass and position as a representation of all the information that is available to subsequent processing. Therefore, blobs, or blob descriptions are indivisible units of information.

8.3.3 The effects of pure symmetry on filter responses

A significant property of this type of filter is that it is symmetric along, and at right angles to, its preferred orientation. Where these orientations coincide with the orientational symmetry in the patterns, symmetry is preserved in the filter outputs. Figure 8.1 shows an example of a spatially filtered and thresholded symmetric dot pattern.

Although linear filters can be said to preserve perfect symmetry, it is important to note they do not detect symmetric patterns. The detection of global symmetry requires that pattern elements are explicitly grouped in two dimensions: in the direction of pairing and in the direction of the axis. Oriented filters simplify the image structure in only one spatial dimension, and even within this dimension the filters do not group all of the elements explicitly.

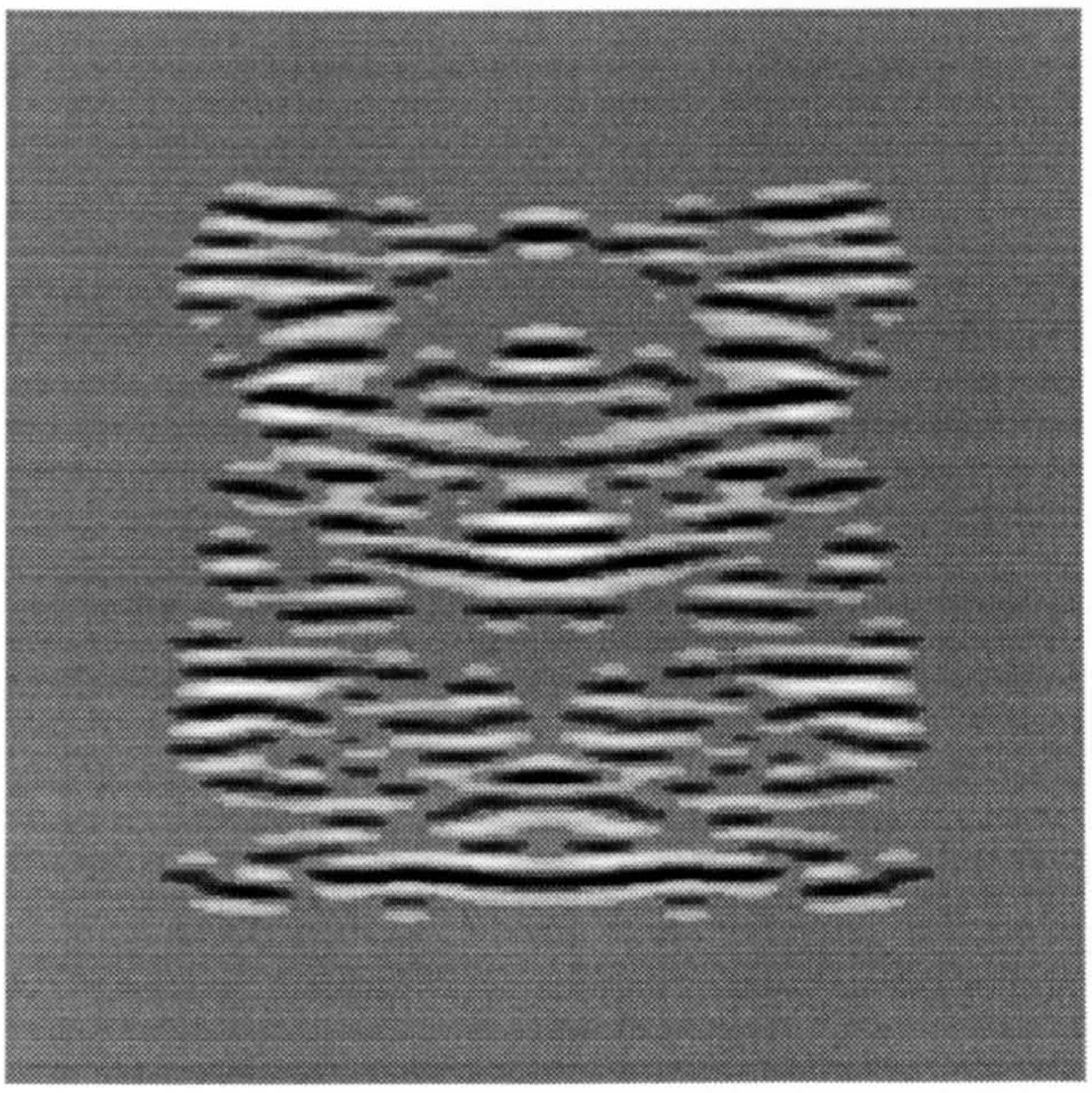


Figure 8.1 A representation of a perfectly symmetric dot pattern at spatial scale 2.5 pixels (filter s.d.).

It can be seen in Figure 8.1 that two types of spatial pattern result from the filtering of symmetric images. The first is a single, elongated blob which is symmetrically shaped and centred on the midline axis. In effect, where this type of response is elicited, the pairwise correspondences are explicitly detected by the filters, through the fusing of the symmetrically positioned elements into a single central feature. The second type of spatial pattern comprises pairs of blobs which are symmetrically positioned, but spatially separated on either side of the axis and which are mirror images of each other. In this case the filtering operation makes explicit the symmetry and alignment of the blobs which emerge from local groups of elements, but does not explicitly solve the correspondence between these. Some explicit matching between the spatially separated blobs is required for the pattern to be detected.

Where a single blob has fused the symmetric pairs together making the pairwise relationship explicit, further matching of pairwise elements is not required. Nonetheless, even where the pairwise relationships are made explicit, it is not the case that the global symmetric pattern is automatically given. The detection of global symmetry requires not only that the symmetrically positioned elements are paired, but also that the symmetric elements are grouped into a single coherent pattern. In perfectly symmetric stimuli, the common relationship between the features is easily detected, as all of the features present in the pattern are symmetric and aligned about a single axis. This relationship is most obvious in patterns which contain fused pairs, as the common correspondence between the fused elements is expressed by a single parameter - the direction of maximum alignment of blobs. Even in perfectly symmetric patterns the strength of this correspondence is variable, depending on the characteristics of the stimulus and the filter functions used.

8.4 Size, scale, and symmetry in dot patterns.

At any point in a dot image, the output of a filter is a function of the number of dots of same contrast falling under the smoothing function and their position relative to the centre of the function. A strong filter response will therefore be elicited by elements which are close in space and aligned at the orientation of the filter. In the case of spatially separated elements which do not fall within the space constant of the same smoothing function, there will be minimal or no combined influence on the filter output.

Where two close elements are symmetrically positioned about a midline axis, a single local filter response is elicited which will traverse the axis. More widely spaced symmetrically positioned elements will not be automatically fused as a result of the filtering process and explicit pairwise matching still has to be carried out, presumably by some higher level process.

It follows from this that a relationship will exist between spatial separation, spatial scale and the likelihood of eliciting fused filter responses. A small filter will produce a strong, fused response to only the very closely spaced pairs of elements in the pattern. Thus, too small a filter is not ideal because the number of possible fused responses is restricted to the few dot pairs positioned close to the axis. This can be seen in Figure 8.2, in which only 2 or 3 dot pairs are fused across the axis.

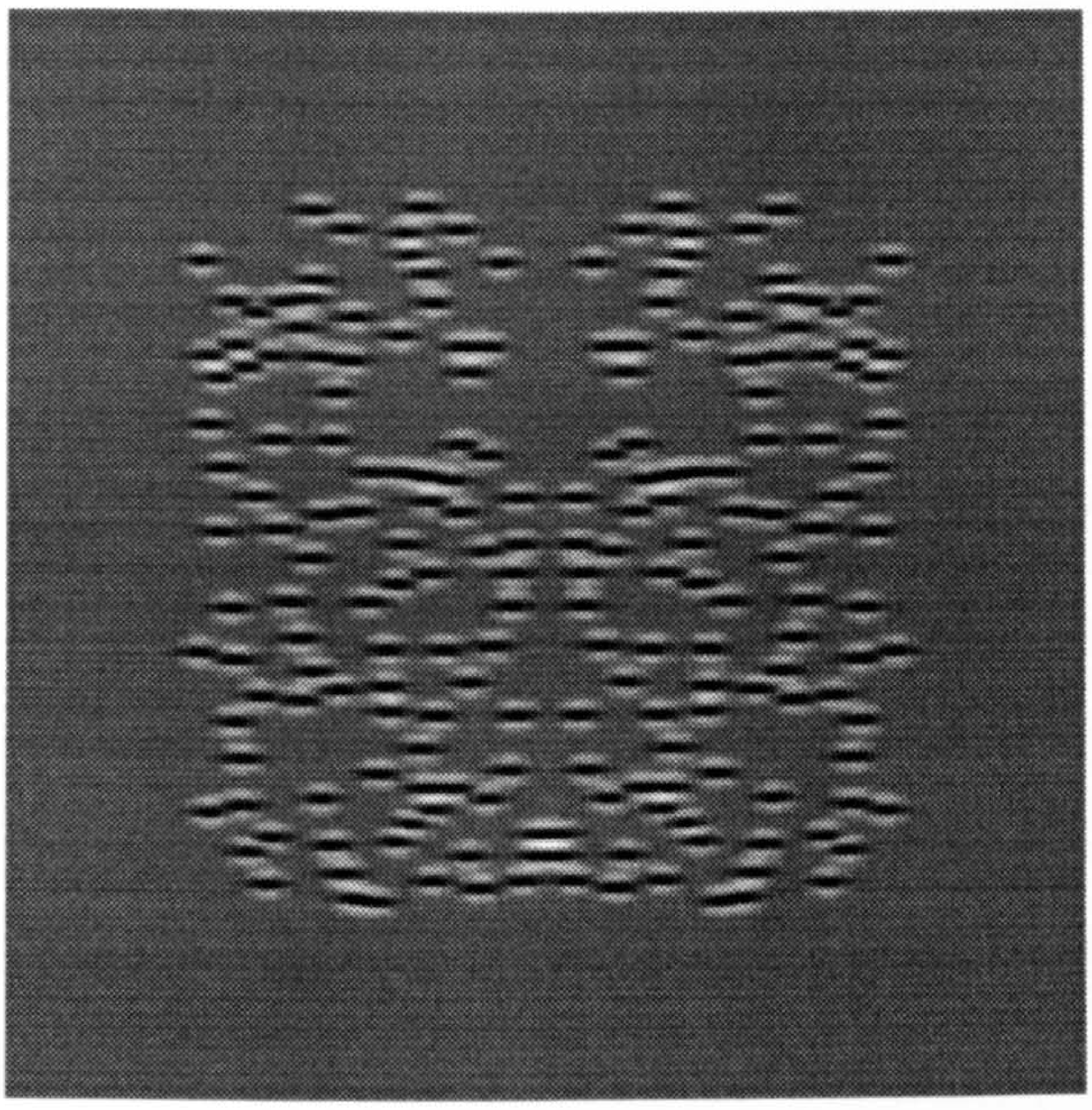


Figure 8.2 A representation of a perfectly symmetric dot pattern at spatial scale 1 pixel (filter s.d.).

Increasing the filter size will increase the range of distances over which elements can be fused. A larger filter will therefore fuse a greater number of element pairs, resulting in an increase in the total number of centroids aligned along the axis.

However, as the filter size is further increased, the number of aligned blobs will eventually begin to fall. It can be seen in Figure 8.3 that the number of blobs aligned about the axis is reduced in comparison with Figure 8.1, due to the larger filter size. The reason for this is that large spatial filters average over large regions of the image, therefore the maximum possible number of aligned centroids is limited by the image size. Large filters also average across local luminance variations in the direction of the axis. This is non-optimal for the reason that variation in luminance in the direction of the axis is necessary for the orthogonal structure to emerge.

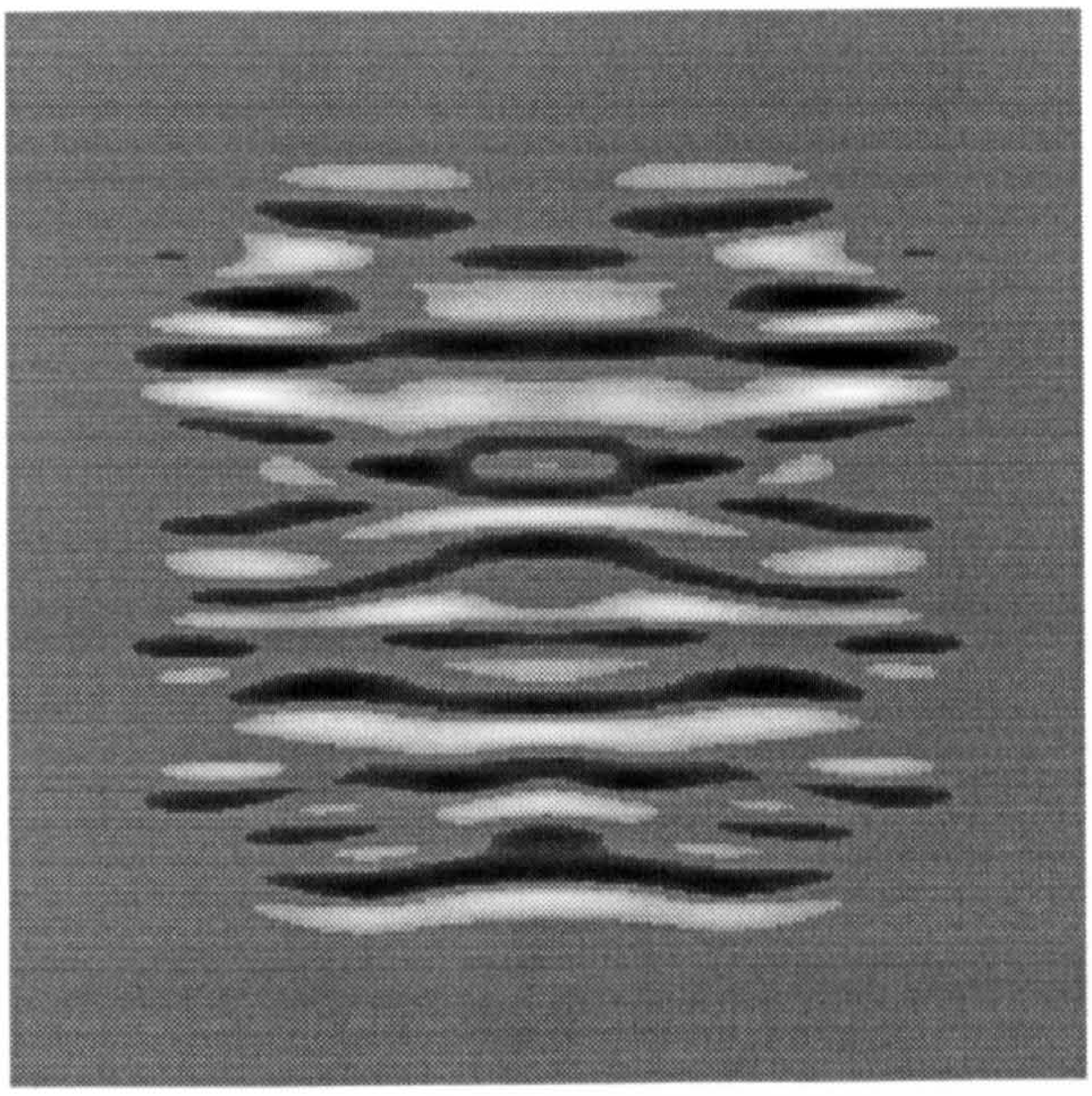


Figure 8.3 A representation of a perfectly symmetric dot pattern at spatial scale 5 pixels (filter s.d.).

Although an ideal filter would be one which fuses symmetric pairs at all separations in the pattern, the optimal size of filter for this task is determined by the variation in filter responses in the direction of the axis, as well as the number of fused pairs. The optimal scale of analysis is one which maximises both the number of fused structures in the filter response and the number of contrast differences in the direction along the axis.

If the elements themselves are increased in size, either as a result of local grouping or by virtue of the pattern characteristics, the value of the elements will more strongly influence the mean value of the local area under the filter. In this situation, a larger filter can be used, and strong filter responses will be obtained at a greater spatial separation.

8.5 Explanation of results in light of filters

8.5.1 The effects of imperfect symmetry on filters

It is proposed that oriented filtering may be an early and automatic mechanism for making explicit the symmetric positioning of point pairs and that the fusing action of the filters aids in symmetry detection by reducing the computational requirements of the task from a 2D matching problem to a matching in one dimension. However, the nature of filter output has only been discussed with respect to perfectly symmetric patterns, in which the correspondences between elements are very obvious, and which would be expected to be detected equally easily be any proposed symmetry detection mechanism.

The purpose of the filtering process is to simplify the image and create a useful representation of the visual scene by making explicit the major trends in the luminance function. However it cannot be assumed that the major trends in the luminance function are directly correlated with the presence of isolated objects. Luminance changes may also occur where objects occlude one another, where patterns or features occur on surfaces, or in the presence of shadows or strong directional lighting. In order to detect the object in the scene, it is necessary to extract the relevant structural information, from that which is due to other unrelated causes. However, this information cannot be extracted at the filtering stage of the visual process. The reason for this is that linear filters are additive in the sense that the combined response of visual noise (random structure) and signal (systematic structure) filtered individually and subsequently added, is equivalent to a single filtering operation performed on an image which contains both signal and noise. Linear filters therefore respond equally to the object of interest in the scene and the surrounding structure in the image and for this reason the perfect symmetry in the filter responses will degrade as the symmetry in the image is disrupted

The validity of any visual mechanism such as the one proposed here can be tested by disrupting the visual cues it purports to use. It should be possible to make very specific predictions about the performance of the mechanism when under stress, from patterns of human detection performance observed under similar sorts of disruption, and vice versa. Common patterns of deterioration should be observed in both the alignment of filter responses and human detection performance under a range of disruptions on the symmetric patterns.

It is predicted that subjects will detect symmetry best in those stimuli where fused responses with perfectly aligned centroids are produced. The stimulus conditions tested in the experiments introduced a variety of disruptions to perfectly symmetric patterns.

It was established in the experiments of Chapters 4 and 5 that the detection of symmetry in dot patterns is disrupted by adding uncorrelated dots to the symmetric stimulus.

Two methods for disrupting the perfect symmetry in the target patterns were used in the experiments. The first method was to embed the target patterns in a surround of uncorrelated noise dots (encroaching noise). The second was to lay a distribution of uncorrelated dots on top of the target pattern such that the uncorrelated dots fell between and around the symmetric pairs, diluting the symmetry in the pattern (noise dilution). Detection performance was found to be less severely disrupted by encroaching noise than by noise dilution. The two types of noise generate two distinctive types of disruption on the orthogonal and aligned patterns of response which are found in filter responses to symmetric patterns.

8.5.2 The effects of encroaching noise

Embedding the patterns in a noise surround has the effect that uncorrelated dots merge with the symmetry at the edges of the pattern, thereby distorting the perfect symmetry of the existing response. The nature of the disruption created by encroaching noise is that the centroids of the blobs are randomly shifted from the central axis position, disrupting the alignment of the centroids with respect to the axis and to one another. Filter responses to a symmetric pattern with 0, 50 and 75% encroaching noise can be seen in Figure 8.4. The determination of a single symmetry axis requires that some relationship between these randomly shifted blobs be detected. The amount of disruption caused by encroaching noise is a function of the relative sizes of the target and surround regions, therefore increasingly smaller targets should be increasingly difficult to detect under this type of noise disruption. In Experiment 4, where the proportion of signal to noise dots was high and the relative size of the target area was large, near perfect detection performance was obtained. However, as the ratio of the target area to the surround was reduced, the perfect symmetry of the targets became increasingly difficult to detect.

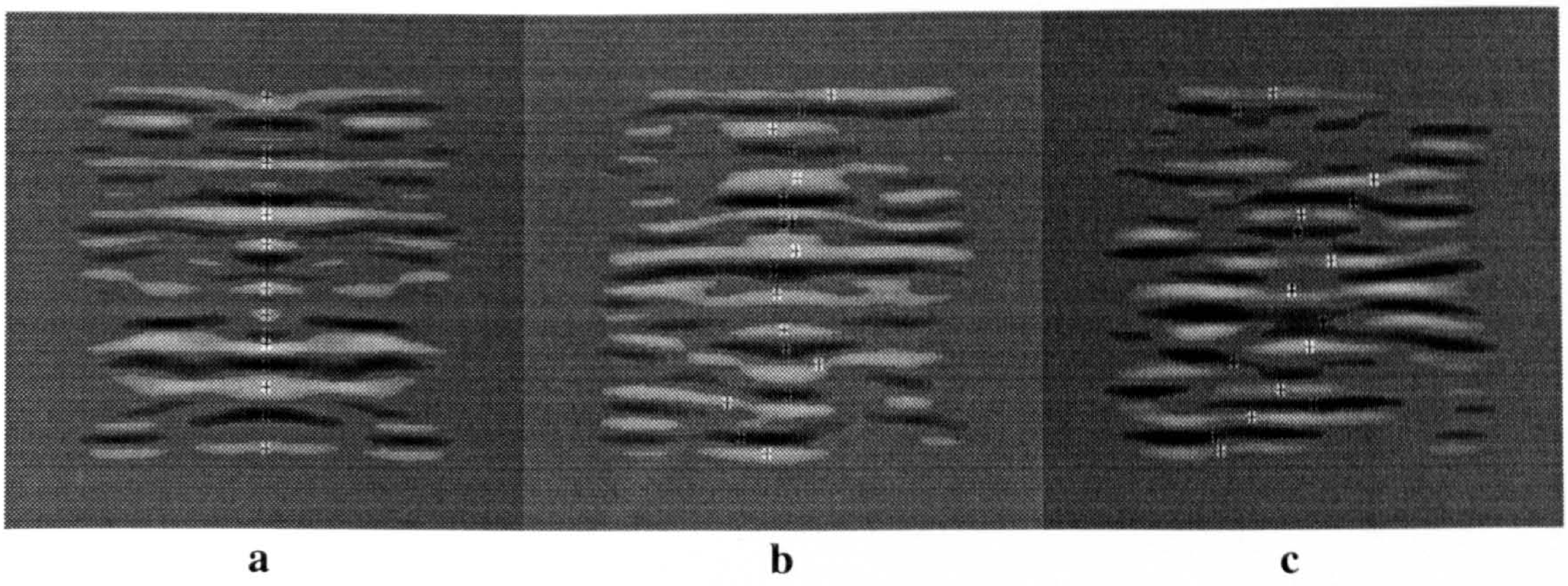


Figure 8.4 An example of the effect of encroaching noise on the alignment of filter responses about the central axis. Panel a contains no noise, panel b contains 50% noise and panel c contains 75% noise. The centroids of blobs which traverse the axis are marked. Spatial scale is 5 pixels (filter s.d.).

8.5.3 The effects of noise dilution

The effect of noise dilution of the pattern is to generate filter responses which are additional to, and independent of the symmetric responses and which will themselves be positioned asymmetrically. Filter responses to symmetric patterns with 0, 50, and 75% noise are shown in Figure 8.5. The nature of the disruption created by noise dilution is that it generates non-symmetric responses in the axis region which must somehow be discriminated from the symmetric responses in order for the symmetry to be segmented. It was established in Experiments 1, 2 & 3 that noise dilution of the symmetric target causes a decline in detection performance, even when the axis position is known to the subject.

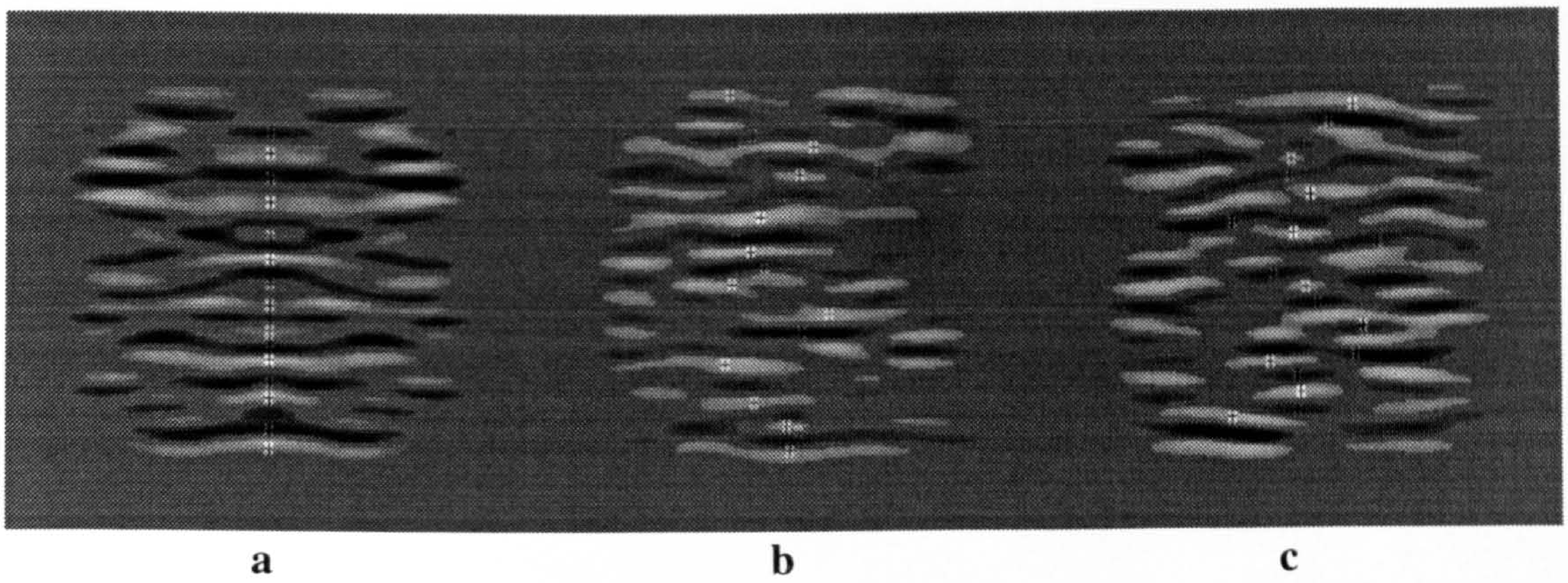


Figure 8.5 An example of the effect of noise dilution on the alignment of filter responses about the central axis. Panel a contains no noise, panel b contains 50% noise and panel c contains 75% noise. The centroids of blobs which traverse the axis are marked. Spatial scale is 5 pixels (filter s.d.).legend

The consequence of both cases is that the perfect alignment of centroids of response along the midline axis is disrupted, resulting in a spreading of centroids about the axis region, only some of which will correspond to the symmetric target. It can be seen in Figure 8.5 that none of the perfectly symmetric blobs in the first panel are unaffected by the noise dilution. Detection of the global symmetric structure requires some method for selecting the most systematic responses. Thus a detection mechanism which uses the alignment of fused blob centroids as a simple, low level cue to the presence of symmetry, would be expected to be error prone under conditions of noise disruption.

8.5.4 The effects of mixing contrast

The fusing of symmetrically positioned pairs under a single filter response requires that the two elements have similar or same luminance values.

Where symmetrically positioned elements are of different or opposite contrast, the local mean value around each will be weighted in different directions. The outcome of this is that the two values will not be fused, but will produce two distinct response regions of opposite sign, which will be symmetrically positioned and which will meet at the midline (see Figure 8.6 showing filter responses to mixed contrast dot pairs with 0, 50, and 75% noise). No fused filter responses about the axis are obtained. A detection mechanism which is based on the positional correlation of fused symmetric elements would be expected to perform badly under conditions in which the pairs are mixed contrast and no fusing occurs. The psychophysical data from the experiments using mixed contrast pairs are consistent with this prediction: detection of mixed contrast targets was found to be poor under the unknown axis condition in both the random dot stimuli and the stimuli containing pairs of mixed contrast discs.

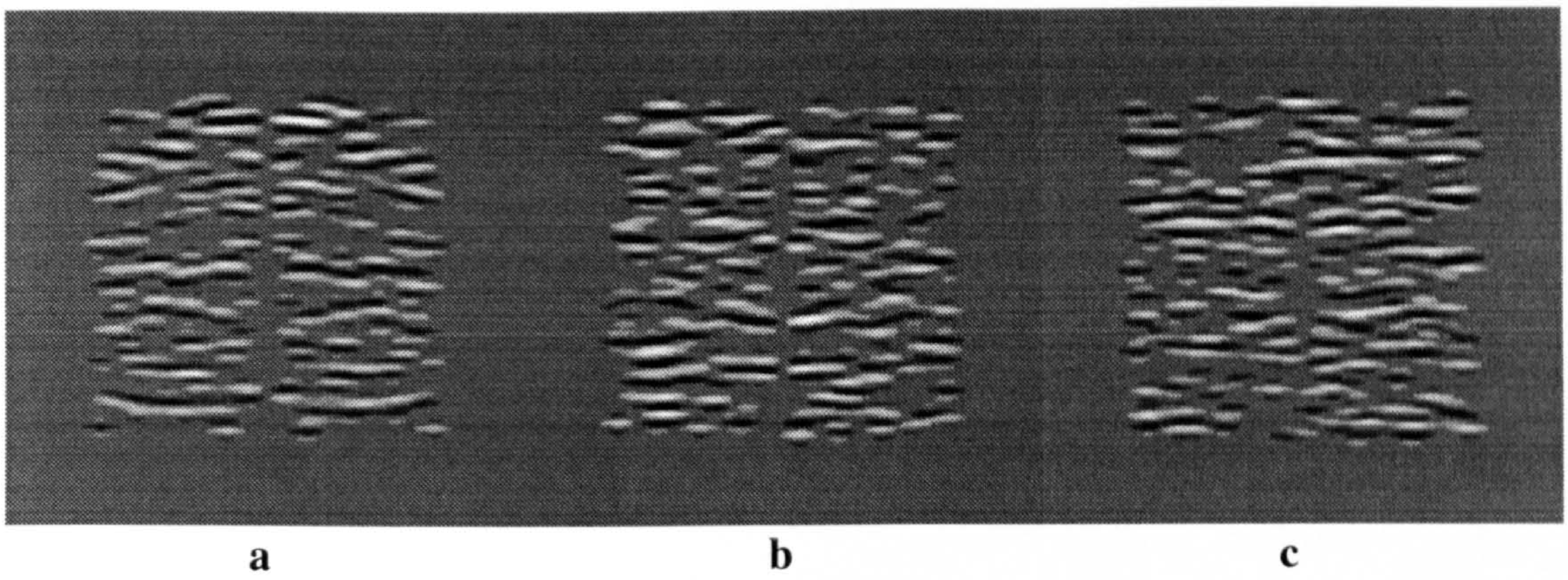


Figure 8.6 A representation of a mixed contrast symmetric dot pattern at spatial scale 2.5 pixels (filter s.d.). Panel a contains no noise, panel b contains 50% noise and panel c contains 75% noise.

Opposite contrast stimuli provide a method for dissociating the use of edge primitives (or zero crossings) from the use of some central measure of a region of response. The fact that symmetry cannot be detected solely on the basis of symmetrically positioned zero crossings suggests strongly that some central measure of response regions is used and that the fusing of elements under a single response region on the axis is important for pre-segmental symmetry detection.

The very high levels of detection performance in the known axis condition supports the conjecture that fused responses are not required to make the point matches explicit when the location of the target pairs is cued by external factors.

Patterns comprised of mixed contrast pairs have an additional disruptive effect on the detection of global symmetric structure. In addition to the requirement of constant luminance in the direction of pairing, a further condition for the emergence of oriented filter response is that variations in mean contrast must occur along the direction of the axis.

Mixed contrast stimuli have the effect of suppressing filter responses across the image. The effect of mixing the contrast of dot pairs in a symmetric pattern is not only to eliminate the presence of fused responses, but also to reduce overall the strength of the filter responses across the pattern. It was established that symmetry detection in uniform contrast patterns is aided by the presence of local clusters of elements. One effect of local clustering is to create local patches of high density which causes a raised local contrast at that point in the image. However the mean variation in contrast is reduced in amplitude if the dots in the local cluster are of mixed contrast, as the mean luminance of a mixed contrast set is near zero.

8.5.5 Filter responses to disc patterns

The effects of noise and contrast described above can also be seen in filter responses to the disc patterns used in Experiments 7-9. Even at full signal, (the maximum of 50 dot pairs), the symmetric structure in the disc patterns was subject to both noise dilution and noise encroachment, as the targets were imposed upon random disc backgrounds, which created a noise surround and a noise background to the targets. Figure 8.7 shows example filter responses to a disc pattern with full signal and it can be seen that these are not perfectly symmetric. Nonetheless, strong fused filter responses are obtained despite the noise. The degree of alignment amongst responses about the axis can be seen in panels b and c. Panel b shows only responses in panel a which touch the axis. Panel c shows the centroid positions of these centrally located responses.

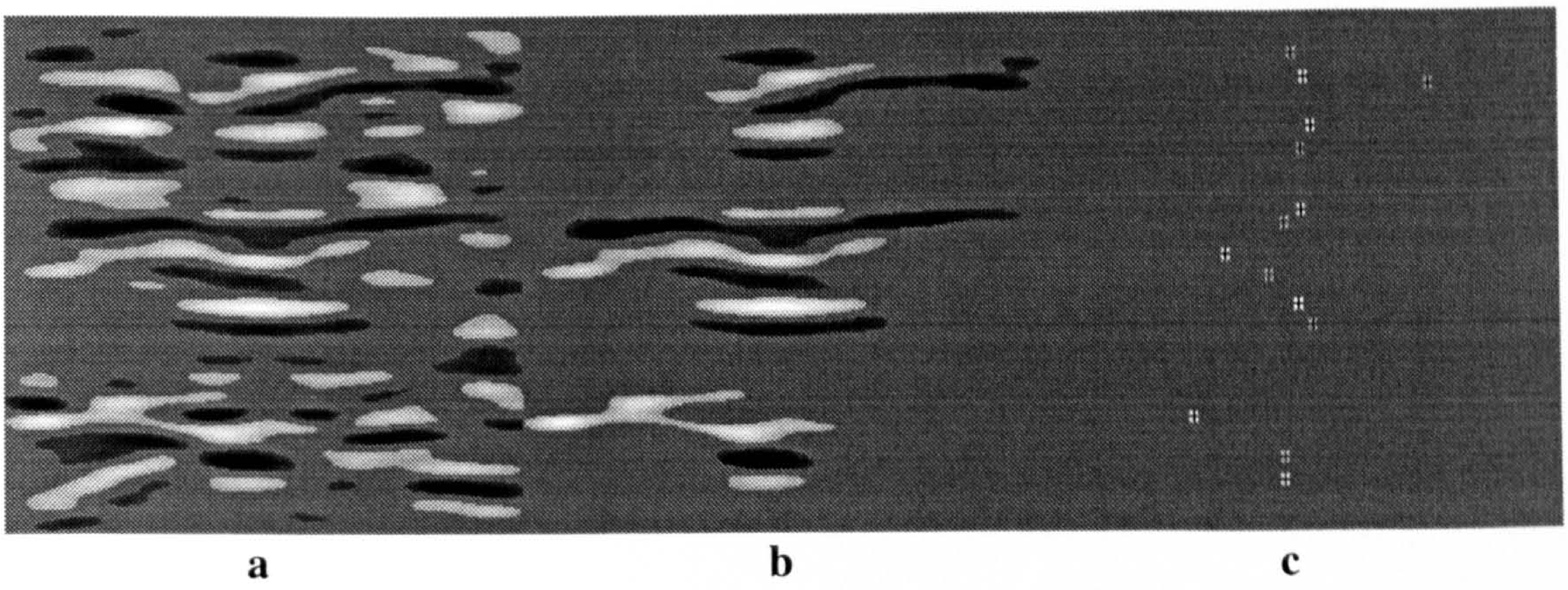


Figure 8.7 Panel a is a representation of a symmetric disc pattern (50 dot pairs, embedded in a noise surround), at spatial scale 5 pixels (filter s.d.). Panel b shows only those blobs which traverse the axis. Panel c shows the centroid positions of the axis blobs.

8.5.5 The effects of mixing size between pairs

The fusing action of oriented filters comes about by the averaging together of regions of same contrast which are aligned at the orientation of the filter. Varying the relative sizes of symmetrically positioned elements does not completely disrupt the contrast uniformity for the reason that the centres of the elements are still aligned, therefore there will be some degree of coincidence of alignment between the areas of the two elements (see Figure 8.8). This coincidence will produce fused regions of contrast uniformity about the axis.

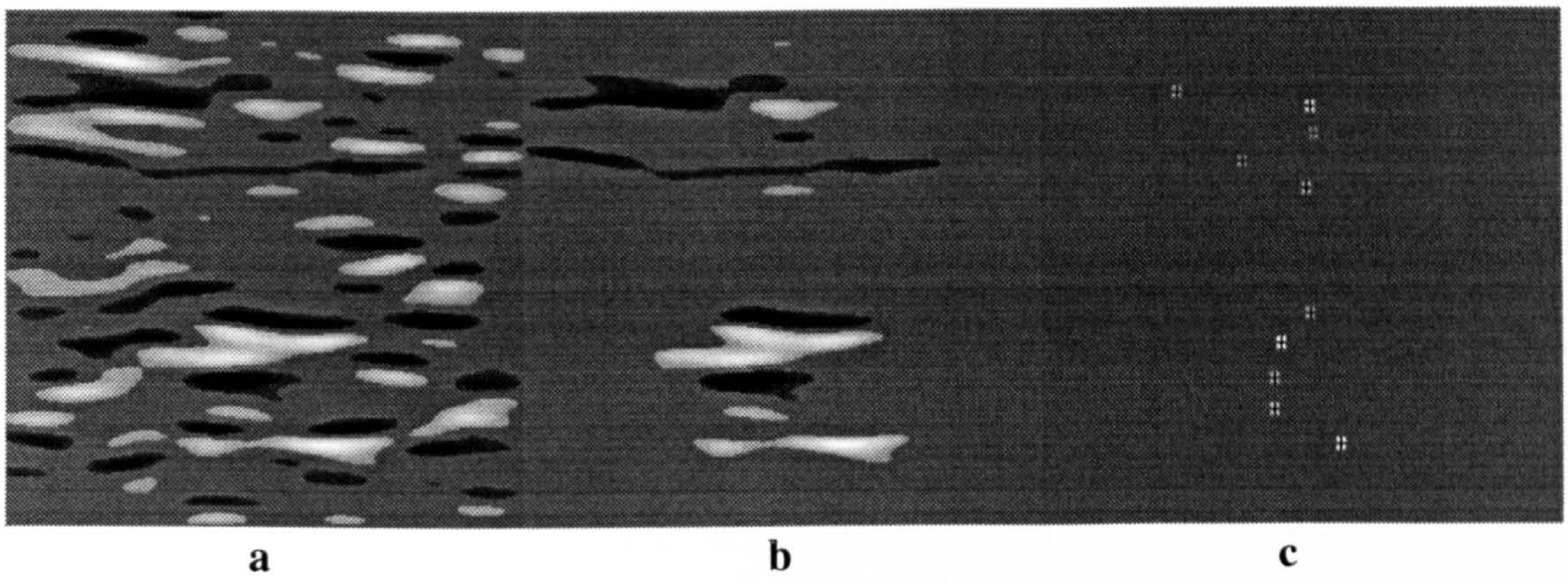


Figure 8.8 Panel a is a representation of a disc pattern (50 dot pairs, embedded in a noise surround), in which matched pairs vary in size. Panel b shows only those blobs which traverse the axis. Panel c shows the centroid positions of the axis blobs. Spatial scale is 5 pixels (filter s.d.).

However, the difference in the size of the blobs will cause the fused responses to be slightly asymmetrically positioned about the axis, as the filter response will be elongated on the side of the larger element. Thus, the centroids of response obtained from fused elements of different size will not be exactly aligned with one another.

The effect of varying element size within was measured in the disc stimuli, and was found to have a disruptive effect on performance, however, detection was still possible. This result suggests that physical differences in the characteristics of the elements only severely disrupt performance where these differences prevent the fusing of elements from happening. The presence of approximately aligned, fused responses is sufficient to support detection of the pattern.

8.5.6 The effects of mixing grey level between pairs

Filter responses to symmetric disc patterns of mixed intensity are shown in Figure 8.9. Even with 100% signal, varying intensity within disc pairs badly disrupts the fusing of filter responses about the axis. It can be seen in Figure 8.9b that some elongated filter responses are elicited in the axis region, however, these responses are poorly aligned with one another, and are therefore more likely to represent spurious structure in the image than symmetric structure. The centroids of these blobs are widely scattered about the axis. It is clear that mixing intensity within pairs disrupts any aligned response in the axis region.

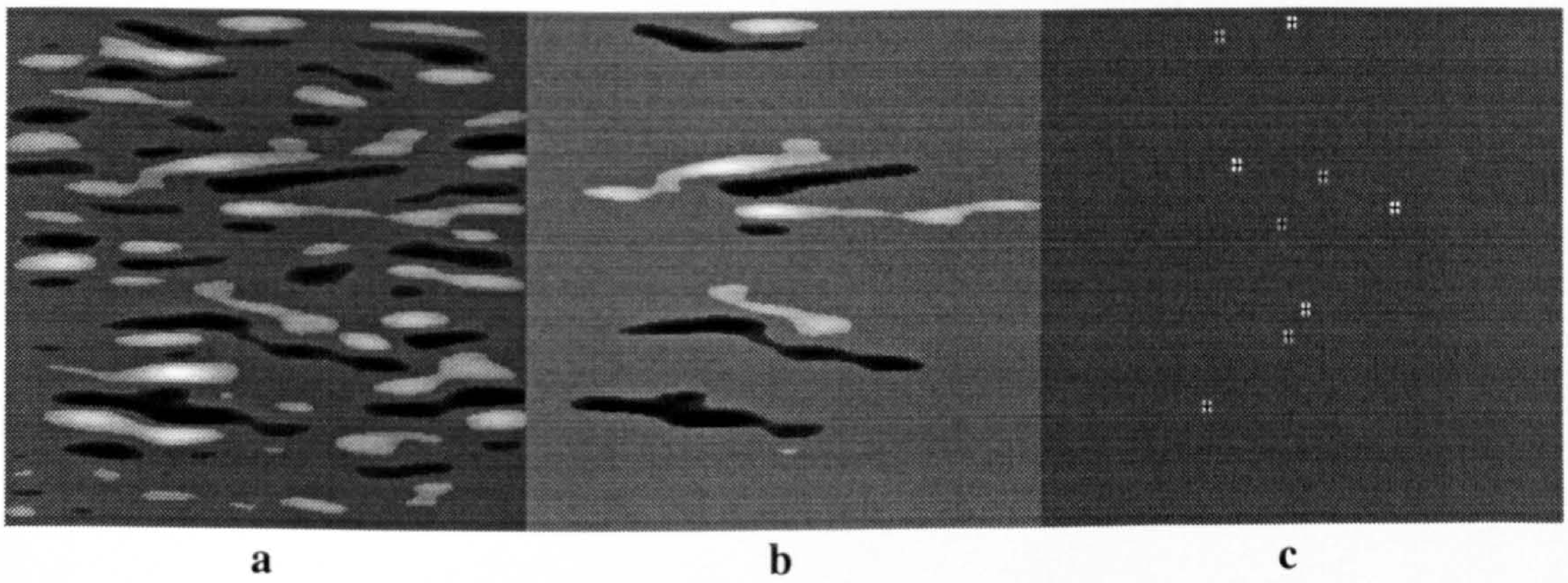


Figure 8.9 Panel a is a representation of a disc pattern (50 dot pairs, embedded in a noise surround), in which matched pairs vary in grey level. Panel b shows only those blobs which traverse the axis. Panel c shows the centroid positions of the axis blobs. Spatial scale is 5 pixels (filter s.d.).

8.5.7 The effect of strings

The effect on filter responses, of placing additional pattern elements between matched pairs along the orientation of alignment, can be strongly predicted from the pattern of results found so far.

In the strings stimuli, the additional elements were placed at random positions between the symmetric pair, effectively disrupting the perfect symmetry of the target patterns, however they had the concurrent effect of strengthening the parallel pattern due to the reasons stated below:

1. Filter responses are obtained, not to *symmetric* elements, but to elements placed along the alignment of the filter.
2. Strong filter responses are obtained to close elements
3. The presence of a global pattern is made obvious by the presence of fused responses to symmetric pairs of elements which are aligned with respect to one another.

In the strings stimuli, the number of potential pairs in the direction of matching was increased by the additional elements. Moreover, the addition of extra pattern elements between the symmetric pair served to reduce the spatial separation between any two elements. The effect of this is that there is an increased probability of two elements of the same contrast stimulating the same filter. In the extreme case, where there is a very high density of elements in a string, a single unbroken filter response will be obtained for each string of elements.

It was noted above that an ideal pattern of filter response would be one in which all symmetric pairings were explicitly fused by the filters. However, by increasing the filter size to include more widely separated pairs, the number of luminance variations occurring in the orthogonal direction was decreased due to averaging in that direction. The optimal filter response would therefore be one in which both the number of fused pairs and the number of orthogonal luminance variations were balanced.

By adding extra orthogonal elements along the direction of pairing, relatively small filters can be used which will elicit strong fused responses in the direction of pairing whilst maintaining maximum luminance variation in the direction of the axis. The pattern of filter responses obtained from the strings stimuli strongly predict that increasing the number of elements in a string should facilitate detection performance. Experimental results show this prediction to be correct.

8.6 The interpretation of structure in natural images

8.6.1 Visual significance and visual models

The results of the series of experiments reported in this thesis provide some indication of the contents of a generalised model of image segmentation. The task of early vision is to extract from a raw image of point intensities, structural features which will be useful in guiding visual actions. Since purposeful actions are typically directed towards objects, the purpose of early visual processing is to make explicit the presence and location of objects in the visual field. There are two requirements of this early stage of vision. First, that the complex and noisy array of point intensities in the raw visual image be reduced into a representation which describes more simply the structure in the image. Second, that this new description of the image be amenable to organisation into perceptual structures which are most likely to correspond to objects.

The contribution of the filtering operation to natural image segmentation is to fulfil the first of these requirements. By averaging local grey level values, spatial filters provide a description of the image which makes explicit only the major trends in luminance. The effect of this is to reduce the number of elements in the image from an array of pointwise intensities, to features of similar intensity. In order to segment this description into object-like structures, it is necessary to organise the given features in a meaningful way.

The perceptual organisation of elements into object-like structures can be achieved by applying a visual model of object structure to the image description, and selecting for further processing those regions which satisfy the conditions of the model. In this way, the visual model brings to bear some level of knowledge about the physical world on the image description. For the purposes of generalised image segmentation, it is necessary that the visual model be able to identify general object characteristics which may guide image segmentation, given any visual scene and no prior knowledge of the scene content.

8.6.2 A visual model of symmetry

Bilateral symmetry may provide the basis of such a visual model. A series of psychophysical experiments has identified a number of pattern constraints which are necessary for pre-segmental symmetry detection to occur. Where these constraints are satisfied, the computational requirements of the detection task are reduced such that a simple computation is found to be adequate for low level pattern detection.

The detection of global symmetry requires in principle that matching be performed along two spatial dimensions. In order to identify symmetric point pairs, matching must be carried out in the direction orthogonal to the axis, and in order to group the symmetric pairs into a coherent symmetric pattern, a further matching must also be performed in the direction of the axis. The purpose of the second grouping is to extract the global pattern from other random structure which may be present in the image, i.e., to segment the object from the background.

It is proposed here that the 2D matching problem posed in symmetry detection tasks is reduced in complexity by the fusing action of low level filtering processes. Those stimulus conditions found to be optimal for detection of symmetry have been shown to produce very distinctive responses in the output of orientation selective spatial filters. Specifically, the responses identified are single, elongated filter responses to pairs of elements which are centrally positioned about the midline axis. This type of filter response automatically performs the correlation between elements in the direction orthogonal to the axis, thereby eliminating the need for explicit matching in that direction.

However, the pairing of symmetrically positioned elements in one dimension is not sufficient for the segmentation of the image into a 2D object description, therefore the spatial filters cannot be said to detect symmetry. Because the position, orientation and size of each object is unknown, any single filter response may be accidental and therefore cannot reliably indicate the presence of object structure. Any pair of elements in the image which elicit a single filter response can be said to be symmetric in the sense that they are in alignment and at equal distances with respect to some axis. Thus the detection of a global symmetric pattern required some further pattern analysis subsequent to the filtering operation, in order to determine the visual significance of the filter responses.

The visual significance of a single filter response is enhanced by the presence of other similar responses which share a common characteristic. The repeated occurrence of a particular characteristic produces regularity, and as a general rule, regularity in images is more likely to occur due to the presence of a meaningful physical structure than by accident.

The purpose of the visual model is to identify a set of characteristics in a filter response which capture the regularity in the image and reliably indicate high visual significance. The model thereby provides some basis for selecting and grouping those responses which are systematic and therefore likely to correspond to objects.

The visual model of symmetric structure proposed here is that those filter responses which are parallel, and aligned about a common axis should be grouped into a single coherent pattern. Thus the position and the extent of the global pattern can be accurately determined by the position and extent of the alignment in the image. The pairwise matching of elements is implicit in this model, as the fusing of symmetrically positioned elements is necessary for the parallel responses to emerge. The advantage of this assumption is that in effect, the 2D matching problem posed by symmetry (pairing and alignment) can be expressed in the single dimension of alignment. Thus the perceptual grouping and the subsequent extraction of the global pattern can be carried out on the basis of a 1D computation which is simpler than the 2D matching that is required to detect both the pairwise matches and the alignment. Moreover, transformations which have a characteristic effect on 2D symmetry will have the same effect on the 1D description of the pattern. The alignment of centroids and common orientation of elements are both preserved under a range of rigid transformations which preserve symmetry, such as movement or rotation in the picture plane. It would be expected therefore that patterns which elicit single elongated filter responses about the axis should be more easily detected under such transformations than patterns which require the transformation to be detected in two dimensions (i.e., explicit pairing of symmetrically positioned elements). Psychophysical evidence suggests that such a detection advantage is found. Strings of elements are easily detected under positional and orientational uncertainty whilst dot patterns are detected only with difficulty under orientational uncertainty and not at all under both positional and orientational uncertainty (Wenderoth, personal communication).

8.7 Natural objects

At this stage it is only possible to speculate about the efficacy of the symmetry model in natural image segmentation. In considering the application of the model to natural images, there are two questions to consider. It is a very broad generalisation to say that objects are 'approximately symmetric' and therefore it must be asked to what extent natural objects are adequately characterised by symmetry. Natural objects are rarely perfectly symmetric, and many symmetric objects undergo non-rigid transformations which do not preserve symmetry. Given this, a visual model which required perfect alignment of elements would clearly fail to detect most natural objects. It is therefore important that the heuristic which is used in segmentation is relatively loosely constrained, such that objects that have a definite axis will produce some sort of response which will be classified as 'coherent' within the bounds of the model. Where the centres of the filter responses do not align exactly, the uniform orientation of the responses (i.e., the parallel structure) will provide a secondary grouping cue, and the experimental results suggest that this is sufficient for pattern detection. Some further research is required to determine the optimum limit of relaxation, as an over-inclusive model would also fail to detect coherent pattern. It is possible that some systematic method for judging alignment could be applied, which relaxes at coarser spatial scales. Many natural objects will not conform to the symmetry model, and will presumably be segmented by the use of other cues such as colour, coherent motion, depth etc.

A further question that must be addressed is whether symmetry can be extracted at a low level in natural images. The symmetry model specifies a number of pattern characteristics which are sufficient for the detection of coherent pattern, but even where these are present, many extraneous conditions will arise in natural scenes to distort or disrupt the pattern. The effects of surrounding noise and noise dilution on symmetry detection have been considered, and the pattern conditions specified as necessary for detection have, to a great extent been determined as those which withstand such noise interference. Other forms of disruption such as partial occlusion of the pattern, strong side lighting, shadowing around the edges of the object and rotation of the object in 3D will disrupt symmetry more severely in ways that have not been considered here

However, natural images are also subject to a number of constraints which are useful to the symmetry model. Many objects are composed of relatively flat, uniform and continuous surfaces which reflect light uniformly. Other objects which are neither flat, not uniform (such as trees) show continuity at a coarse scale of analysis. The symmetry model exploits this general constraint by detecting regions of uniform luminance in the image, attributing these to a common physical cause. Natural images contain information at a range of spatial scales, and objects may be segmented from the background according to the scale at which coherent patterns emerge. By operating on very general constraints such as continuity in mean luminance, the model is relatively resistant to levels of noise interference which might severely disrupt more object specific features, such as shape edges.

8.8 The scope of the model

The visual model of symmetry provides a simple heuristic for presegmental location of coherent structure in an image. Detection performance is judged to be pre-segmental if it occurs without prior knowledge of the size, position or orientation of the pattern in the scene.

It has been shown that only certain types of pattern are easily detected under these stimulus conditions. It has also been shown that those pattern types which are easily detected, also produce visual responses which meet the conditions of the symmetry model. The detectability of different pattern types and their compliance with the model can be explained in terms of the output of pre-segmental visual processing. Thus, it is concluded that the visual model of symmetry offers at least a partial, low level, generalised model of segmentation.

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NUMBERING

AS ORIGINAL

APPENDIX A

Shown here are the pyschometric functions for Experiment 10 (parallel strings condition). Functions for string length 4-8 are given here. The data for string length 2 are identical to those given in Chapter 6, Figure 6.2. Note that as string length increases, the data are presented on a smaller abscissa.

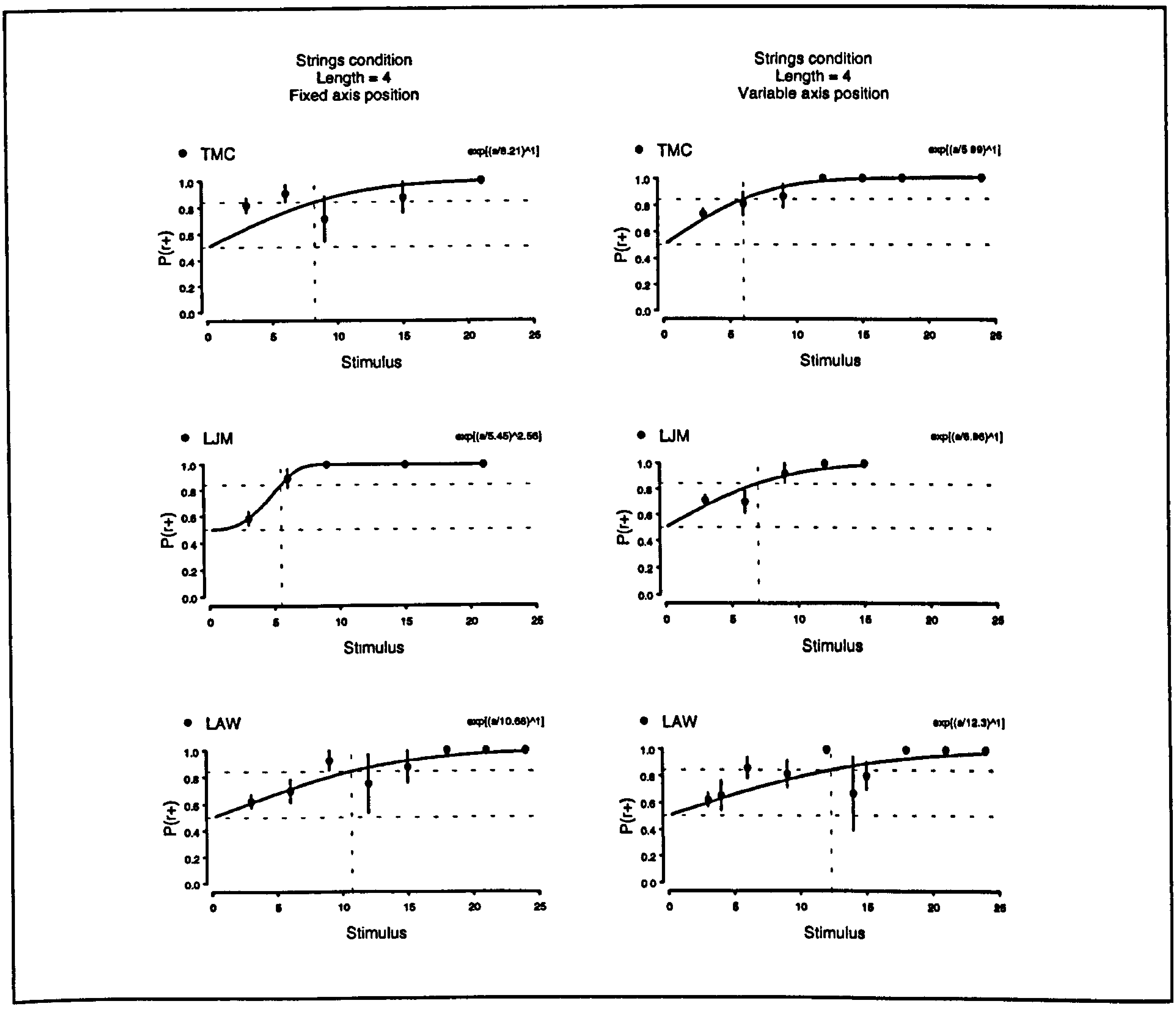

Figure A1. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

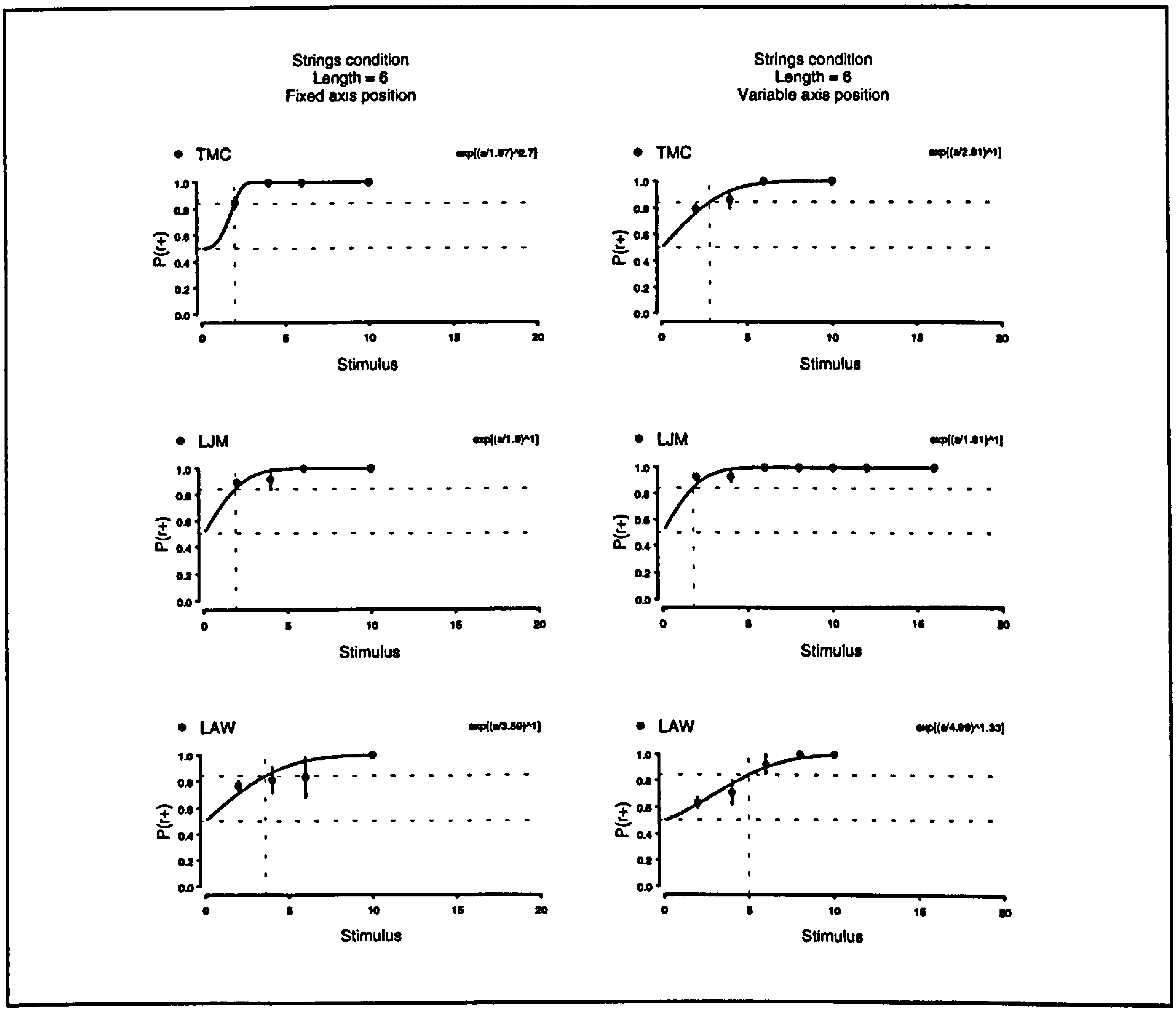

Figure A2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

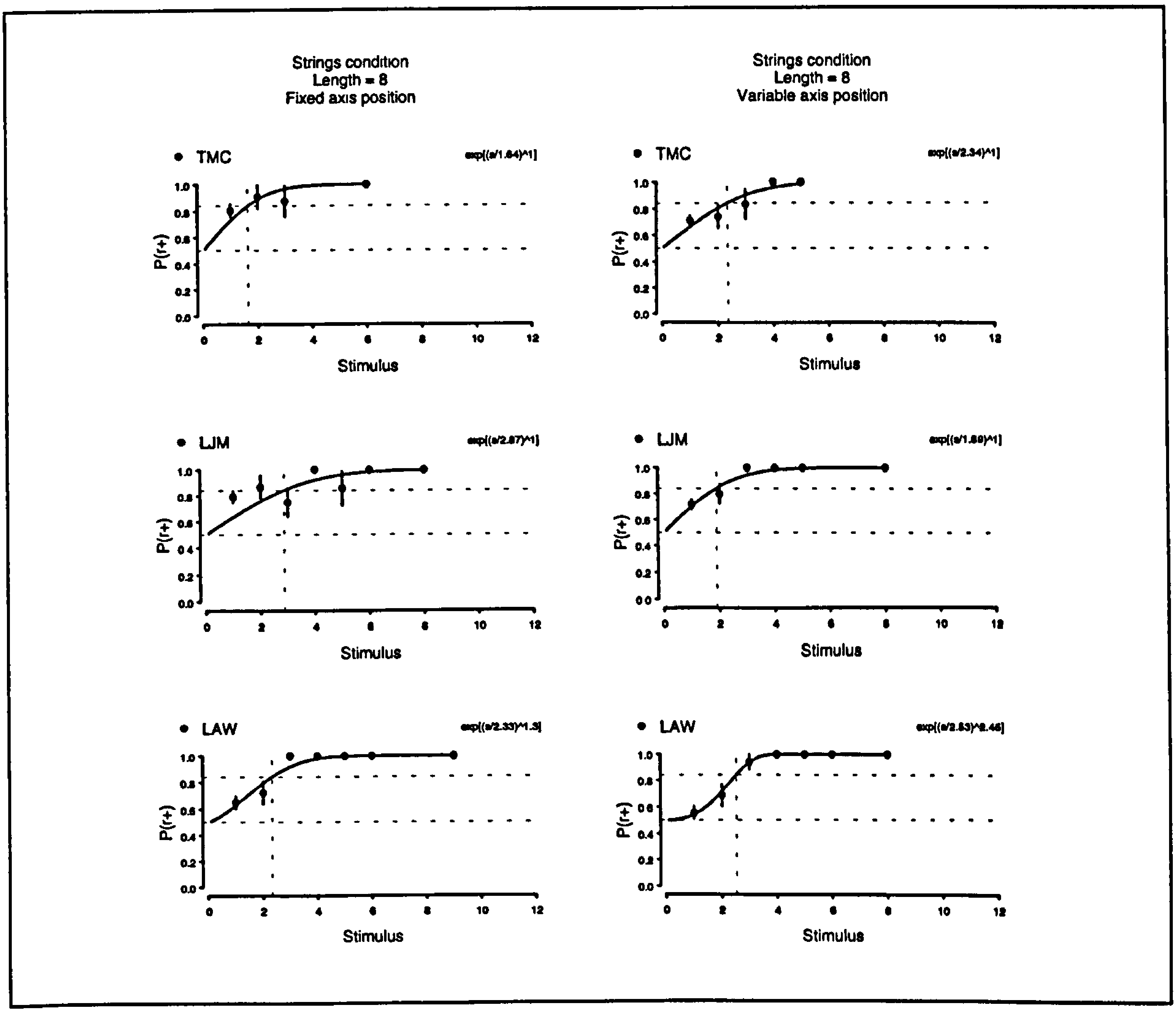

Figure A3. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

APPENDIX B

Shown here are the psychometric functions for Experiment 11 (variably sized strings condition). Functions for string length 4-8 are given here. The data for string length 2 are identical to those given in Chapter 6, Figure 6.4. Note that as string length increases, the data are presented on a smaller abscissa.

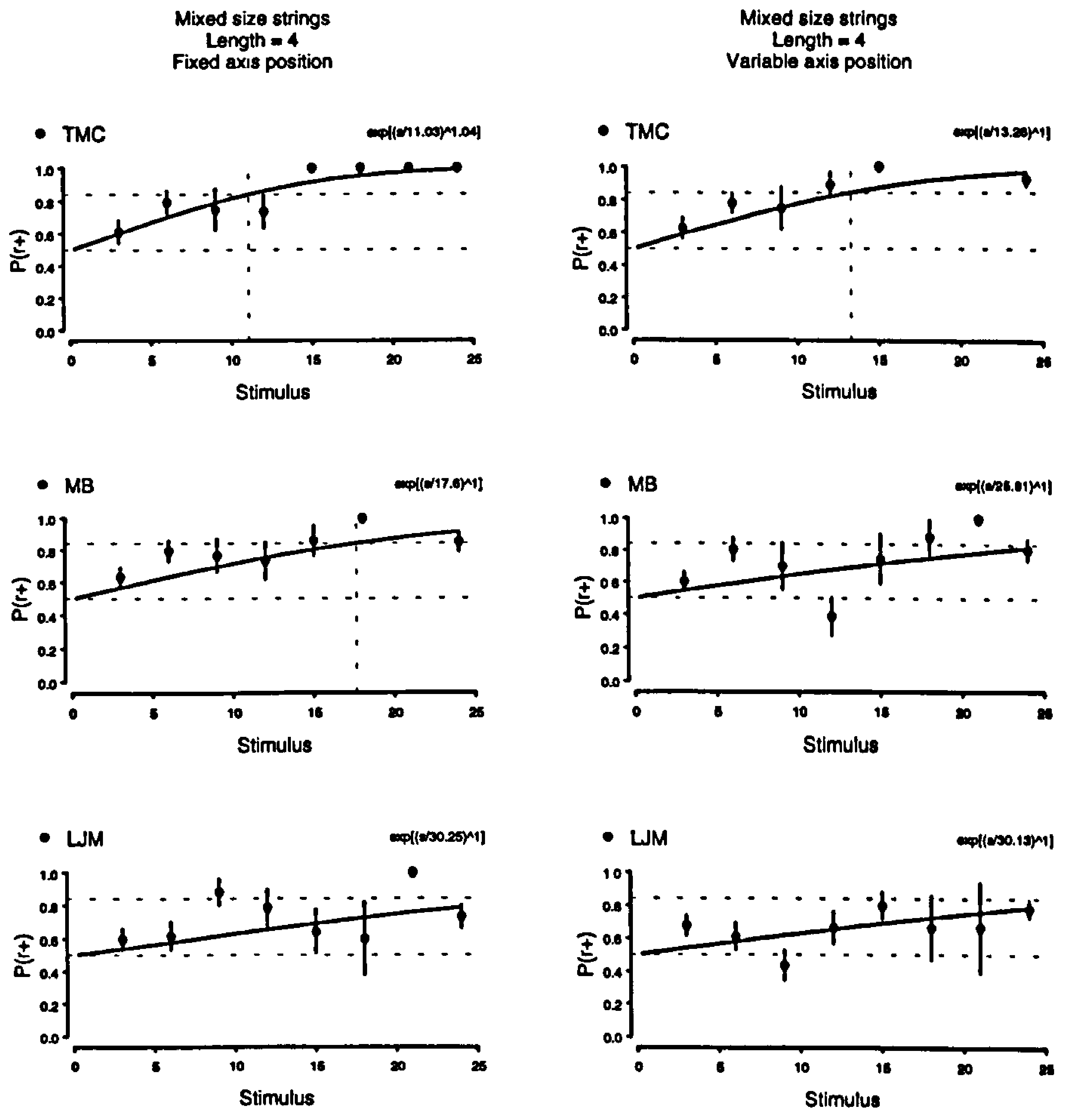

Figure B1. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

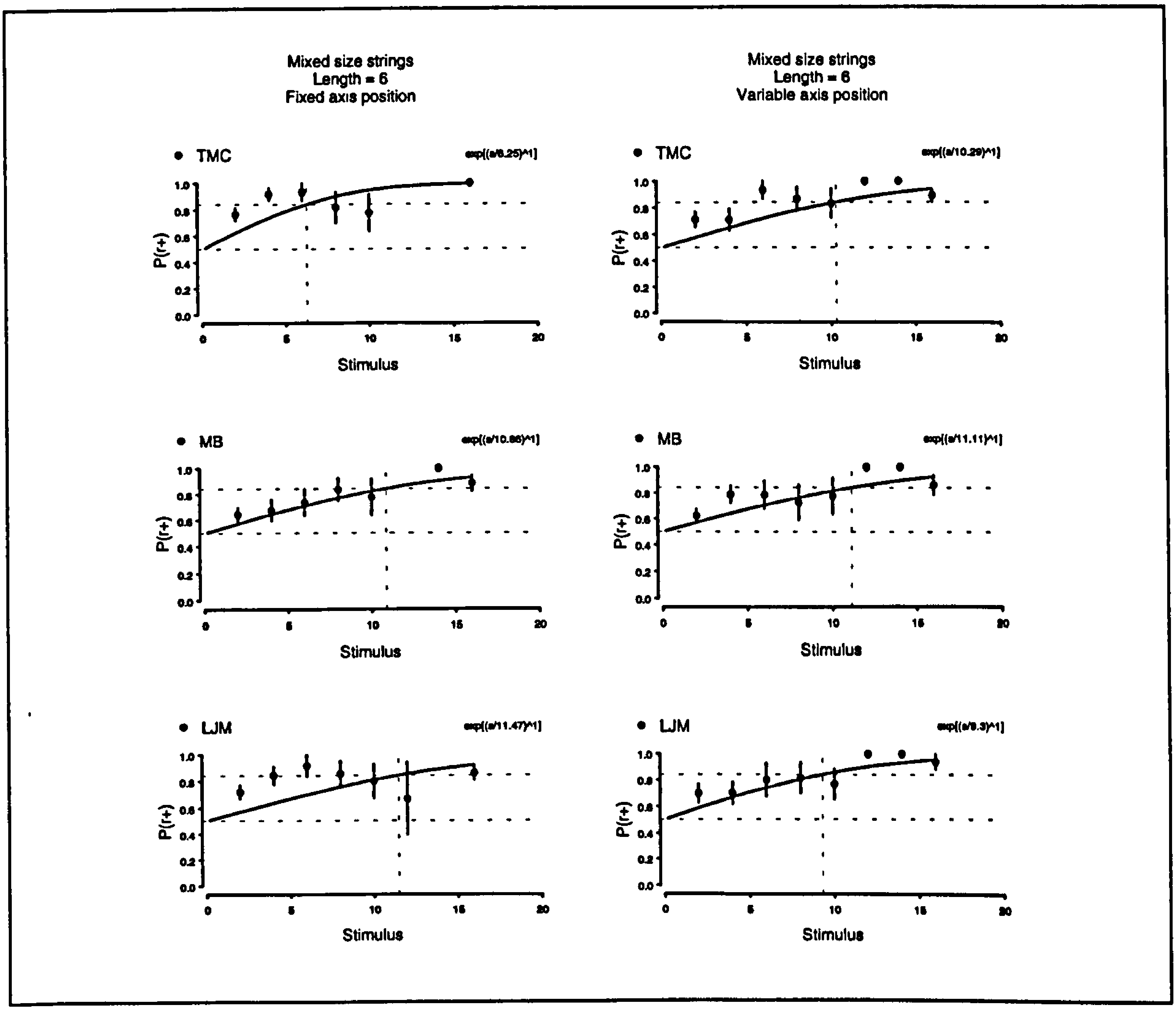

Figure B2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

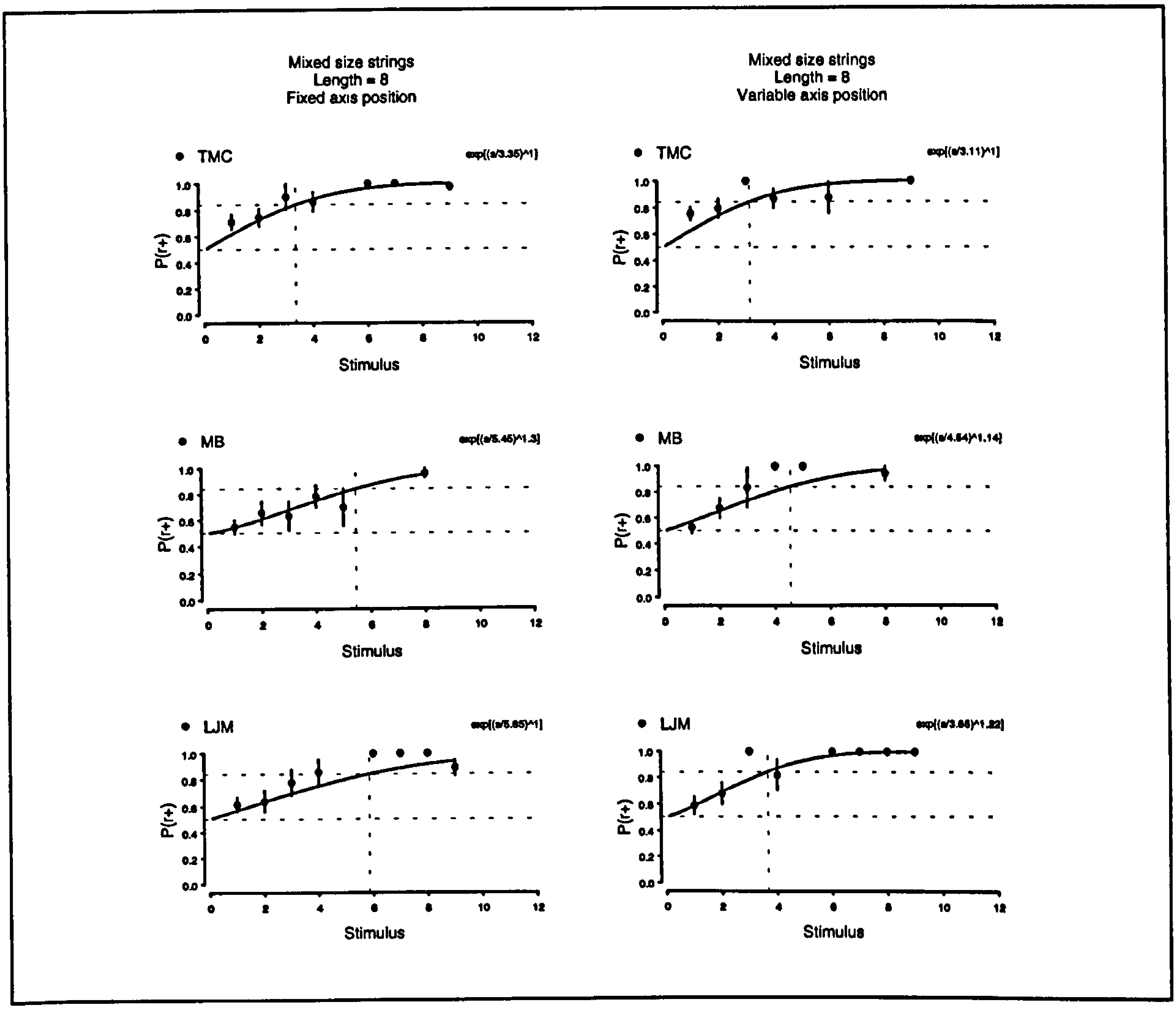

Figure B3. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

APPENDIX C

Shown here are the psychometric functions for Experiment 12 (strings of variable intensity). Functions for string length 4-8 are given here. The data for string length 2 are identical to those given in Chapter 6, Figure 6.6. Note that as string length increases, the data are presented on a smaller abscissa

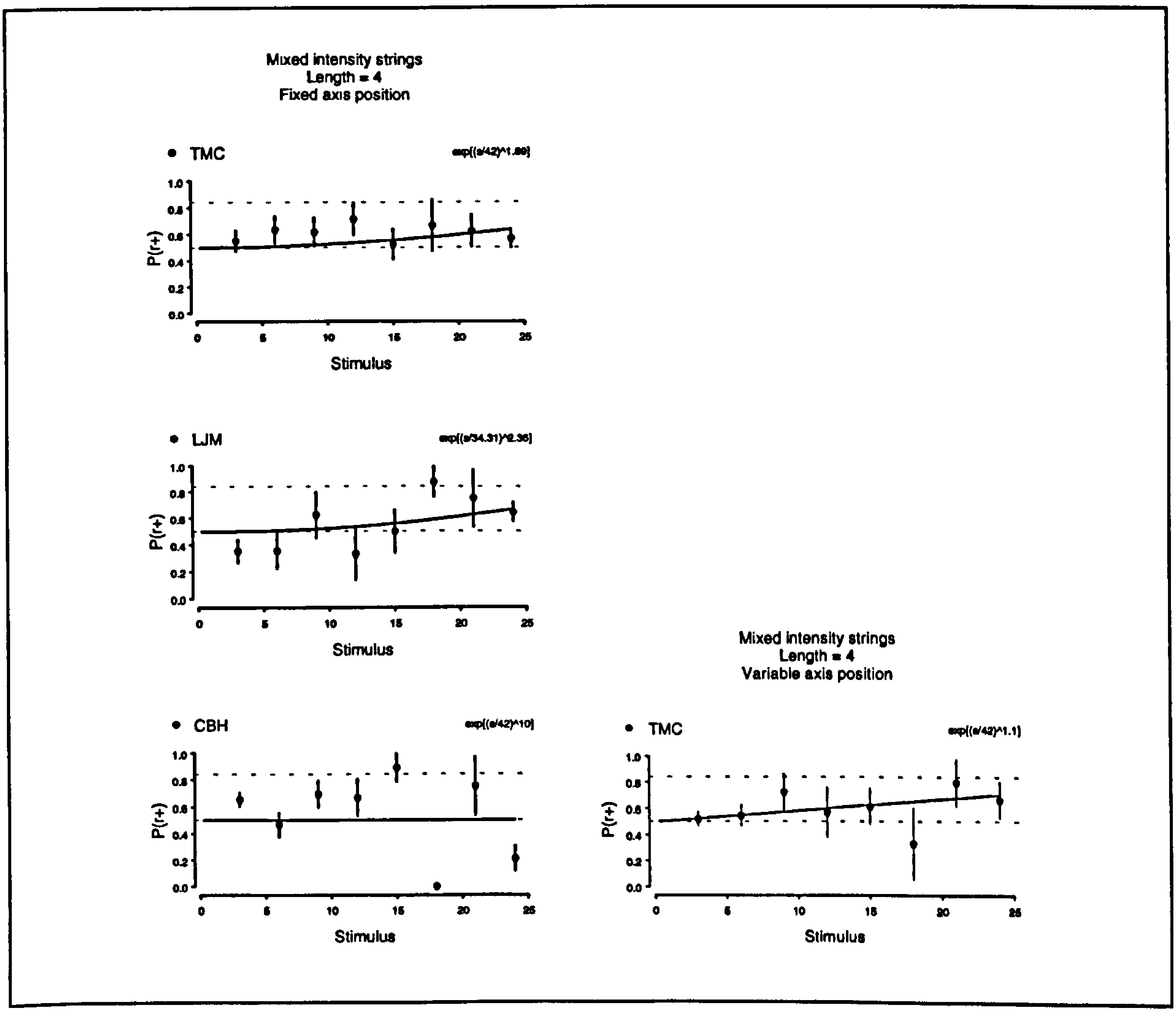

Figure C1. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

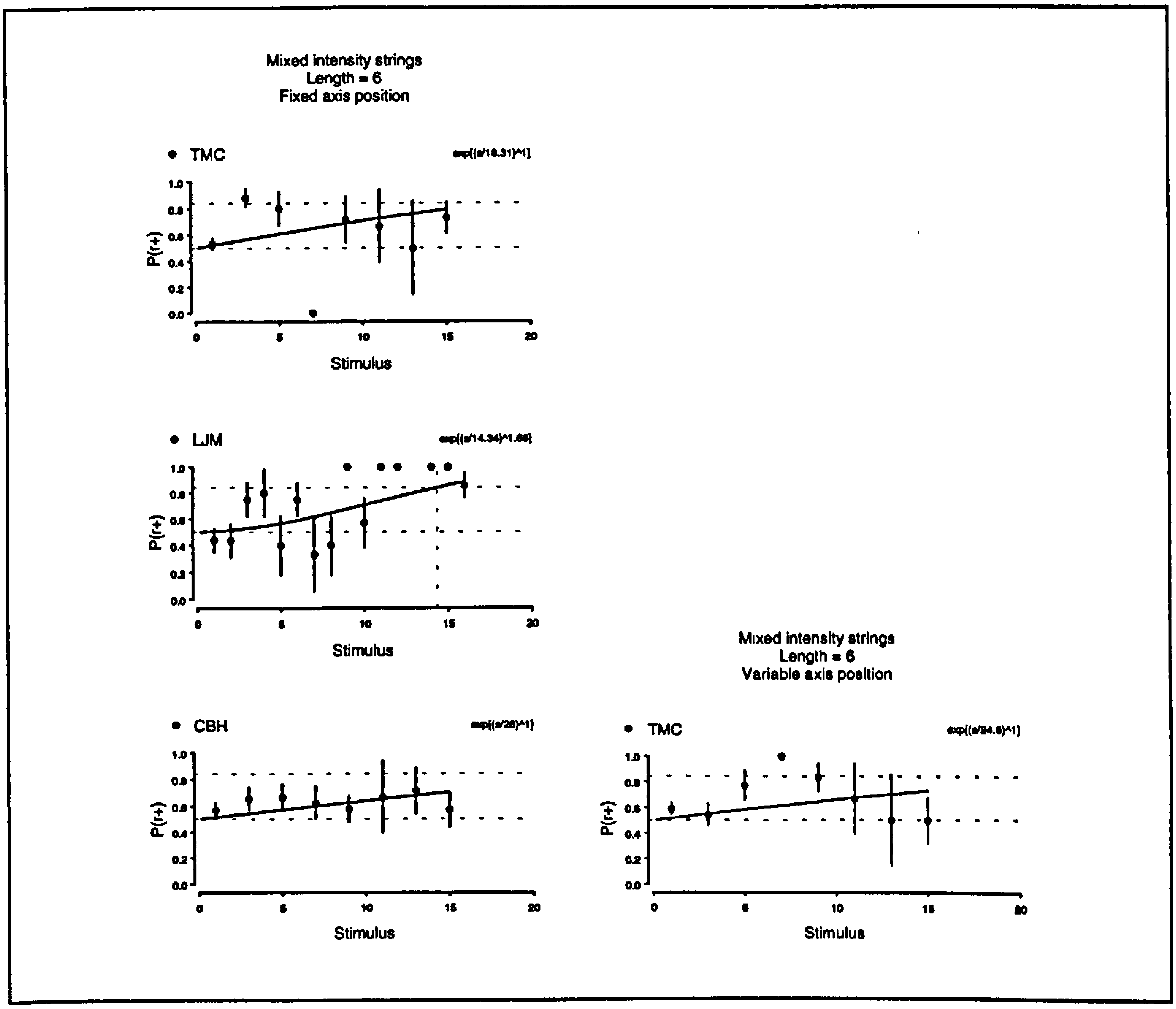

Figure C2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

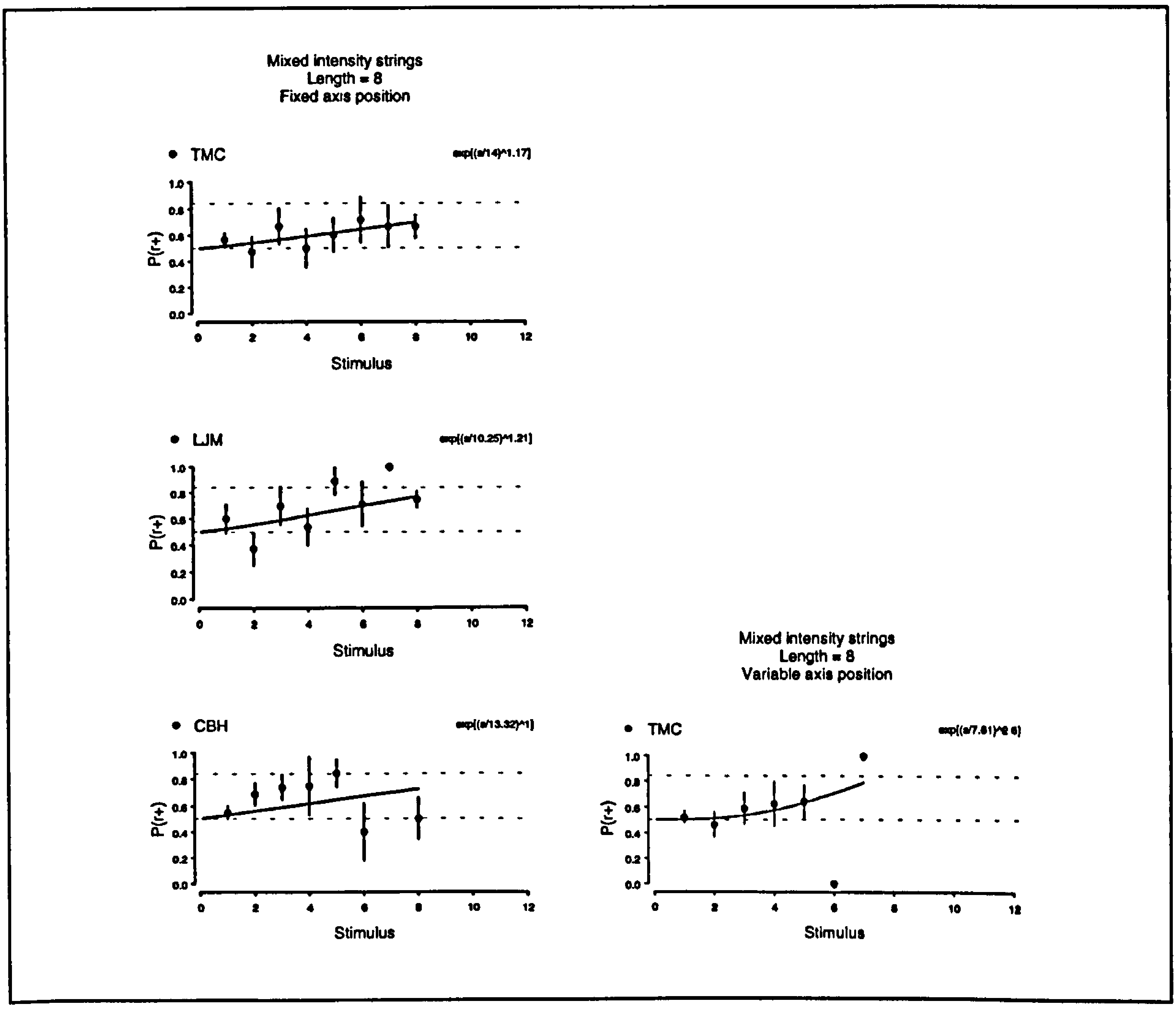

Figure C3. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

APPENDIX D

Shown here are the psychometric functions for Experiment 13 (dot strings). Functions for string length 4-8 are given here. The data for string length 2 are similar to those given in Chapter 4, Figures 4.4 and 4.5. Note that as string length increases, the data are presented on a smaller abscissa.

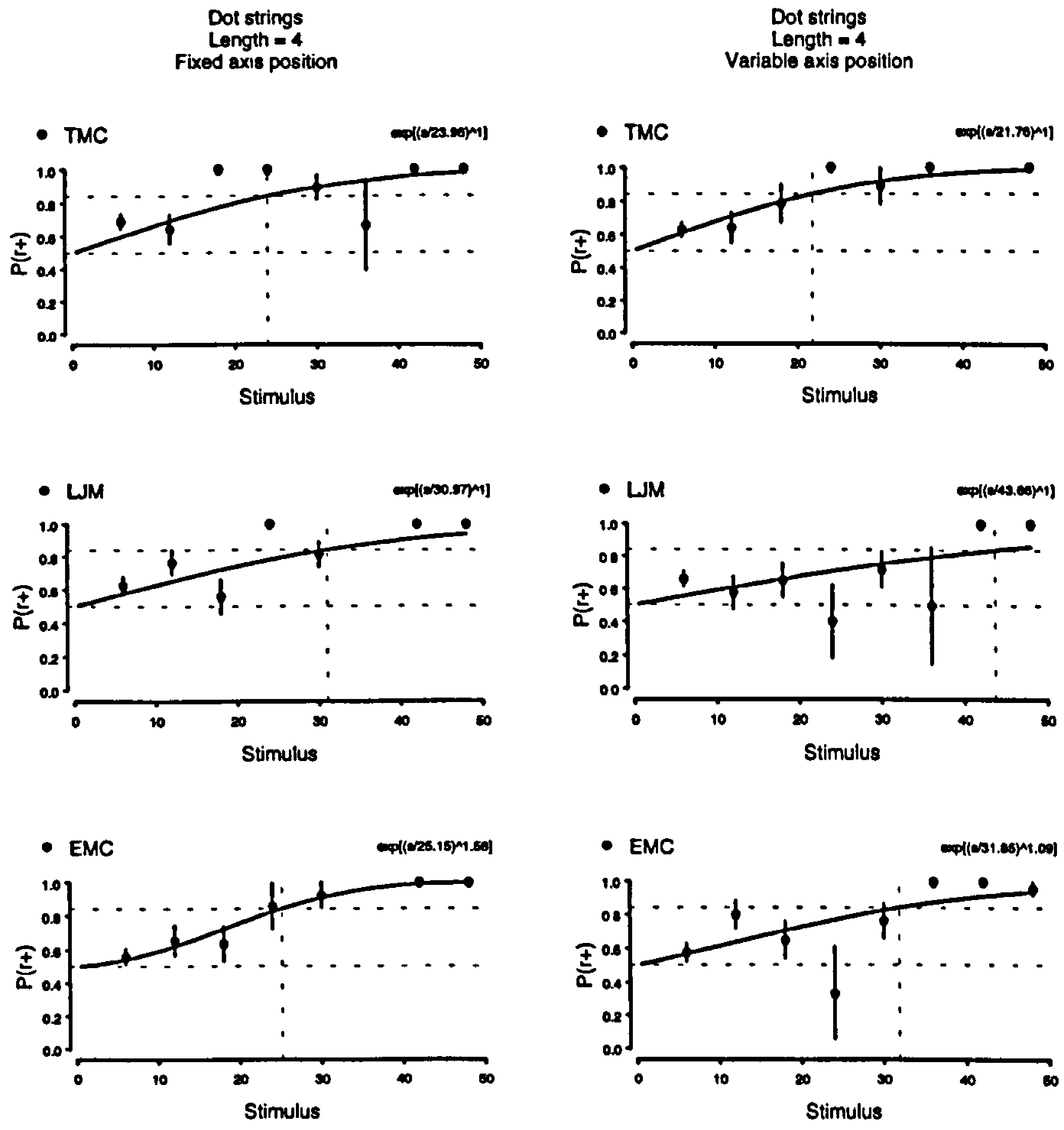

Figure D1. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

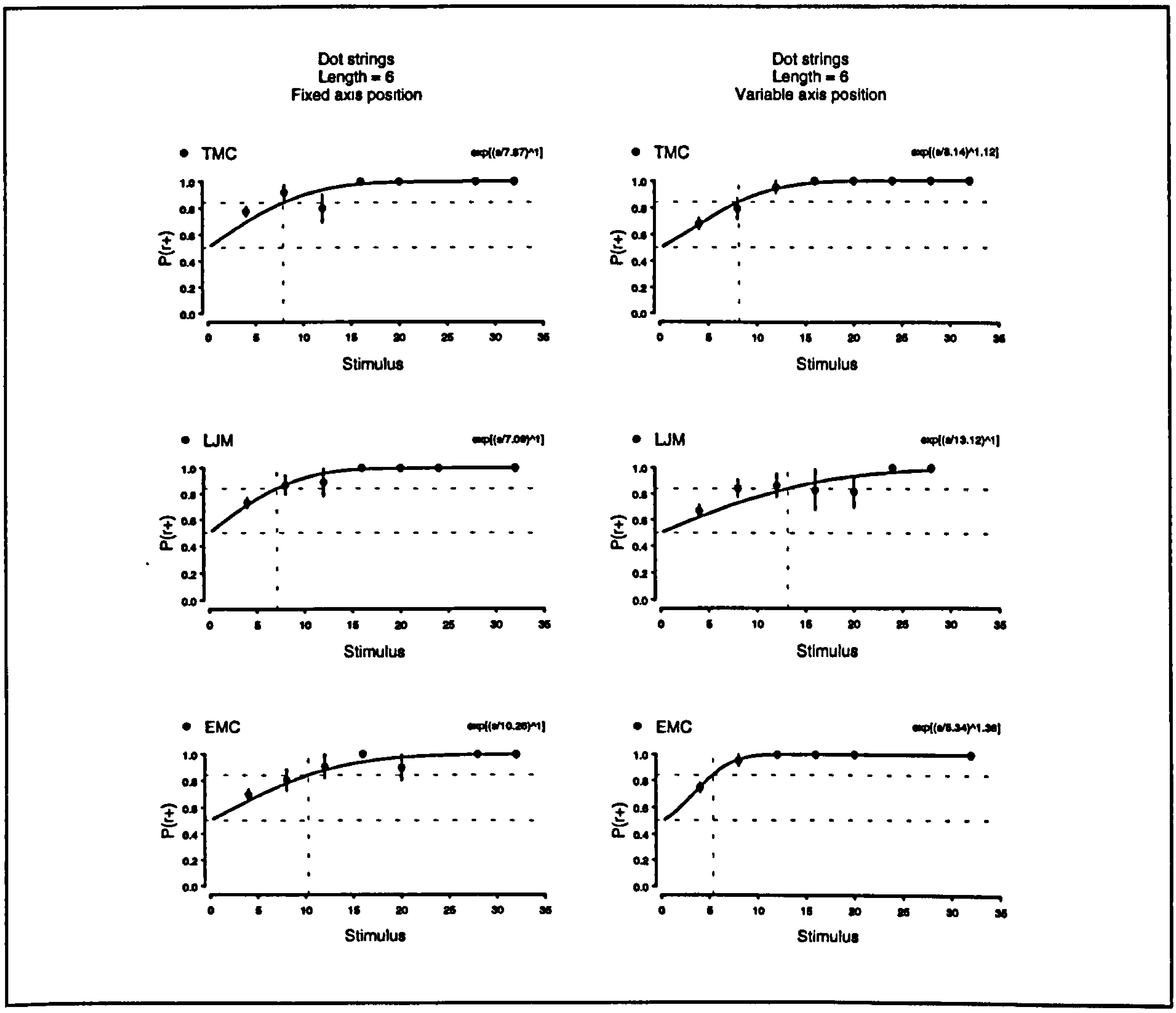

Figure D2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

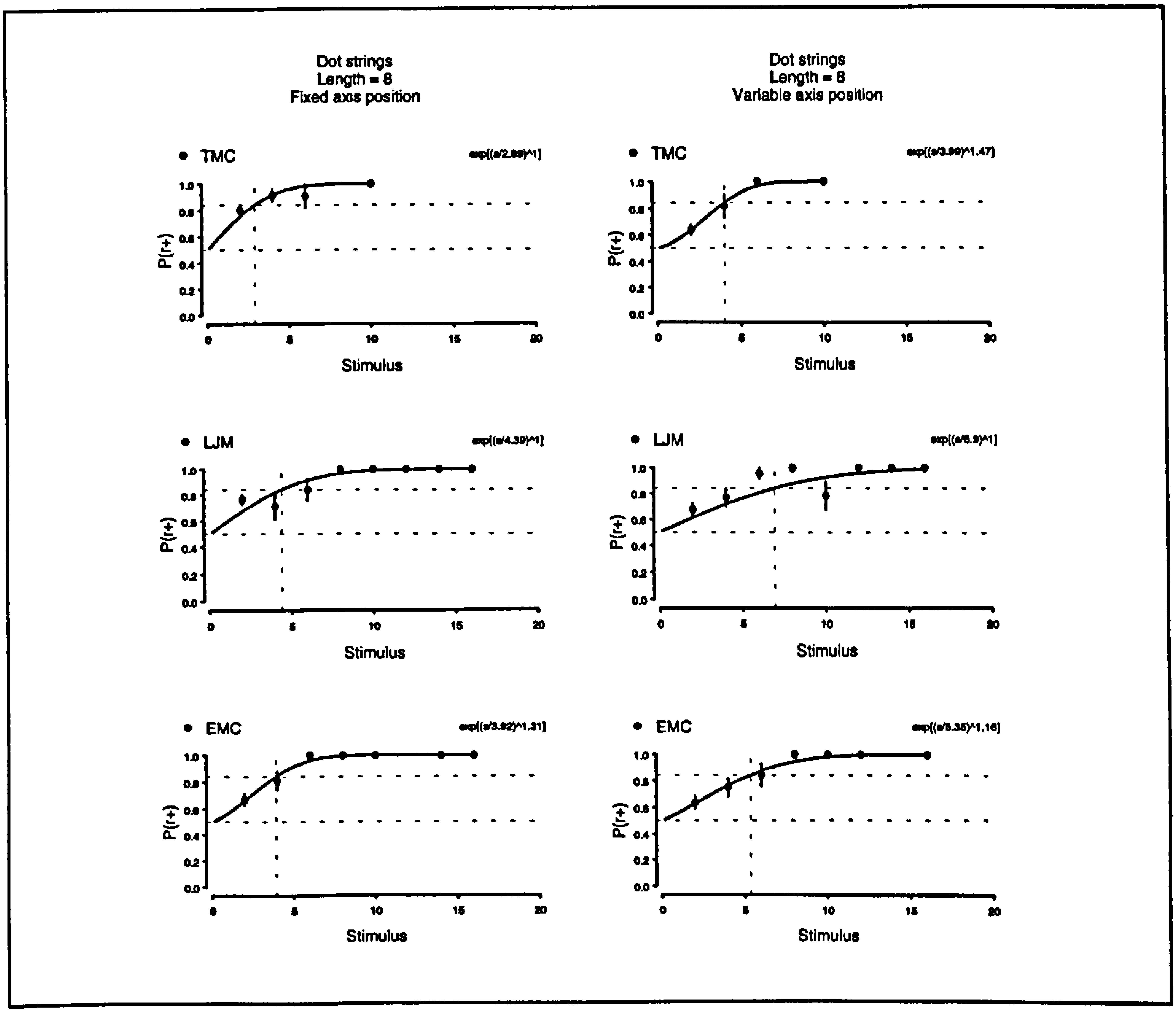

Figure D3. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

APPENDIX E

Shown here are the psychometric functions for Experiment 14 (strings within repeated structure). Functions for string length 2-8 are given here. Note that as string length increases, the data are presented on a smaller abscissa.

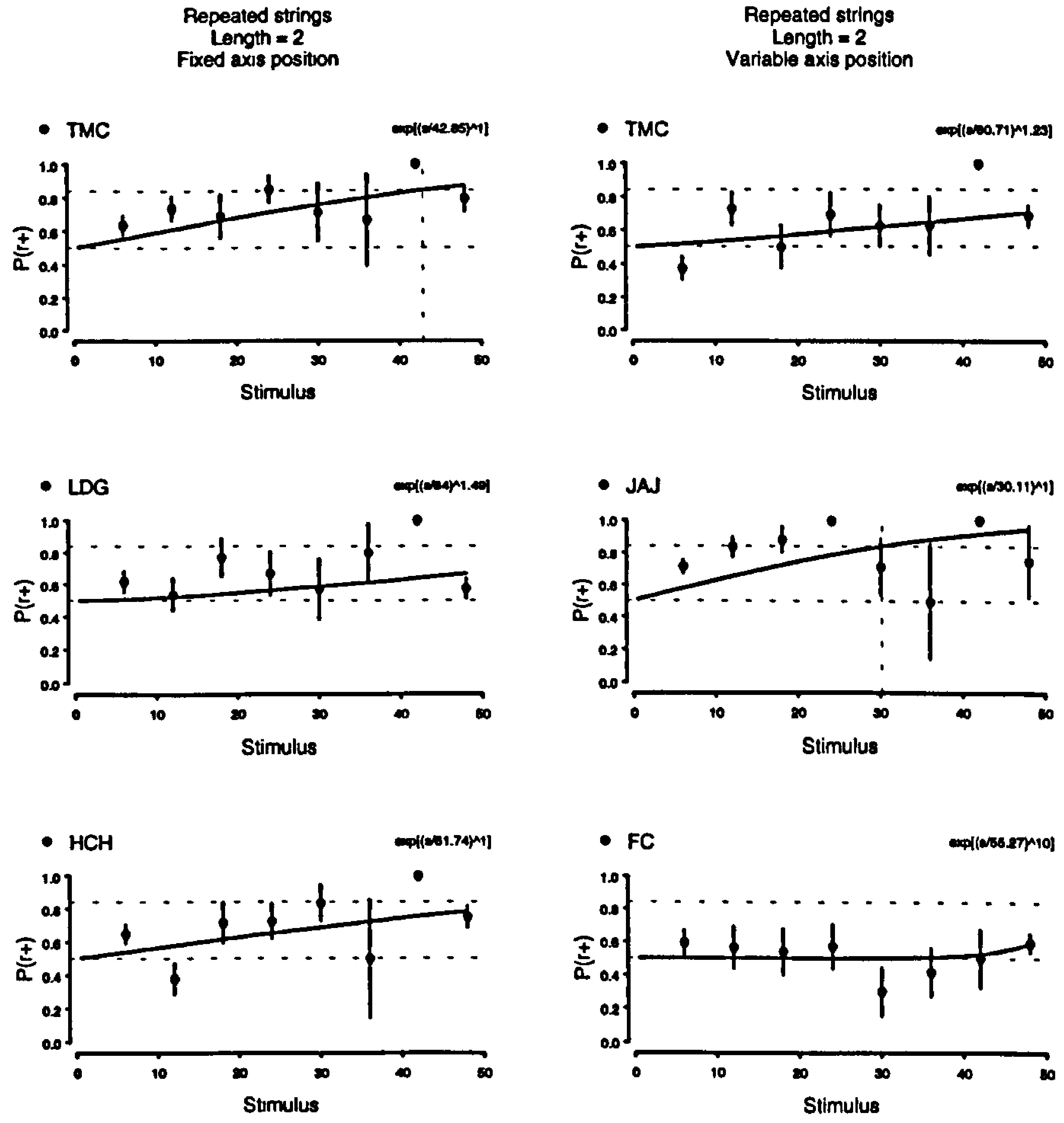

Figure E1. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

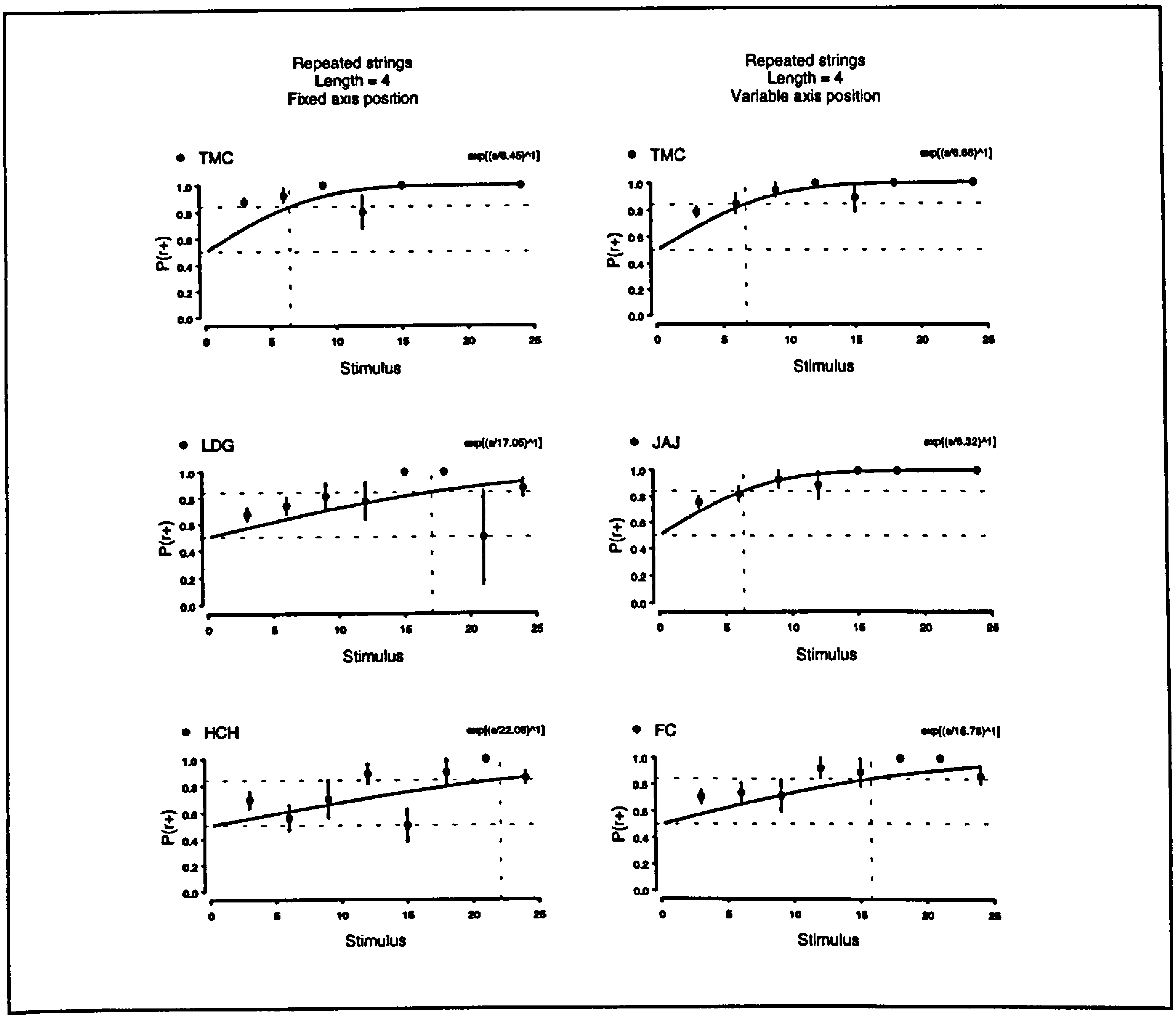

Figure E2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

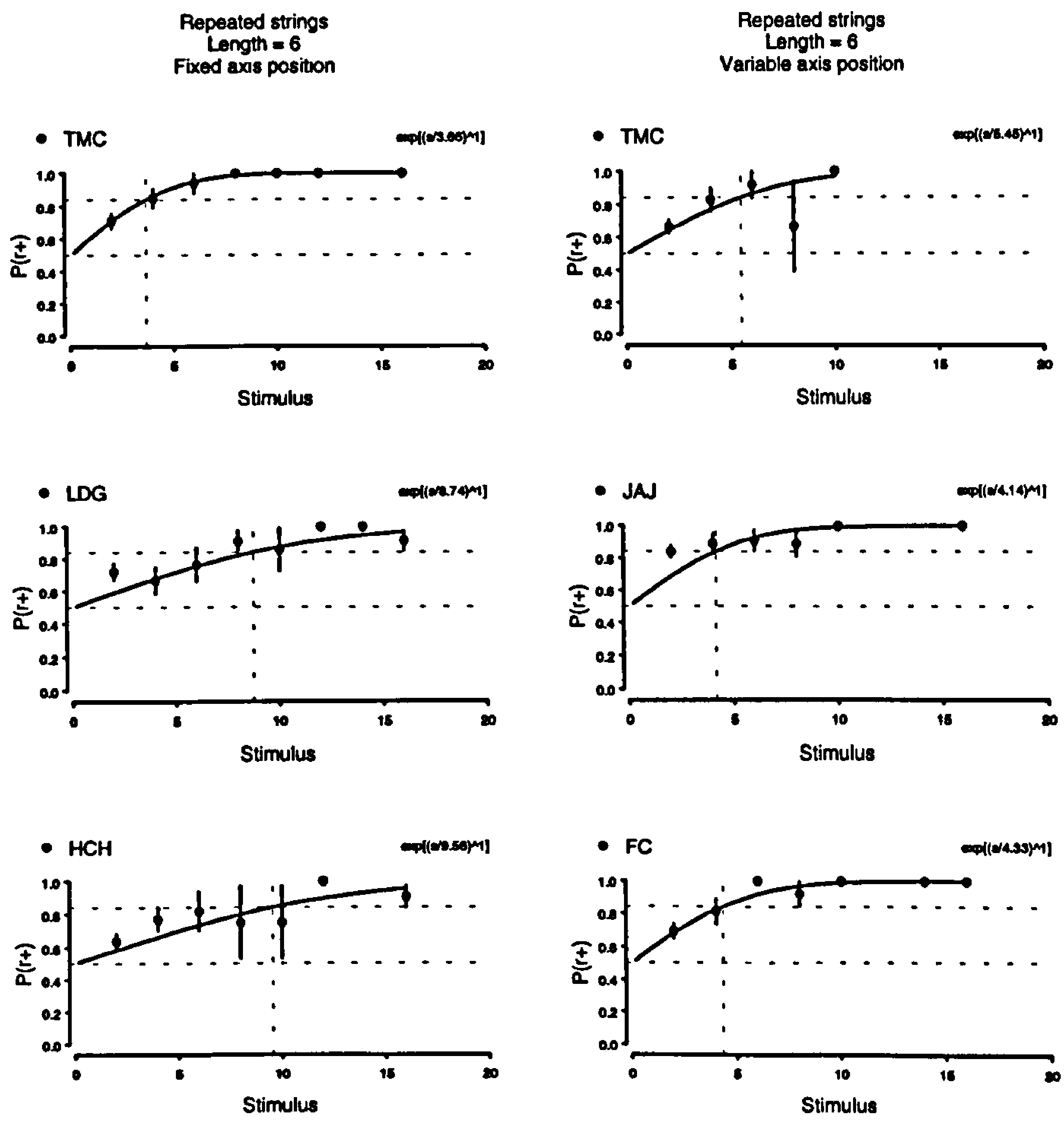

Figure E3. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

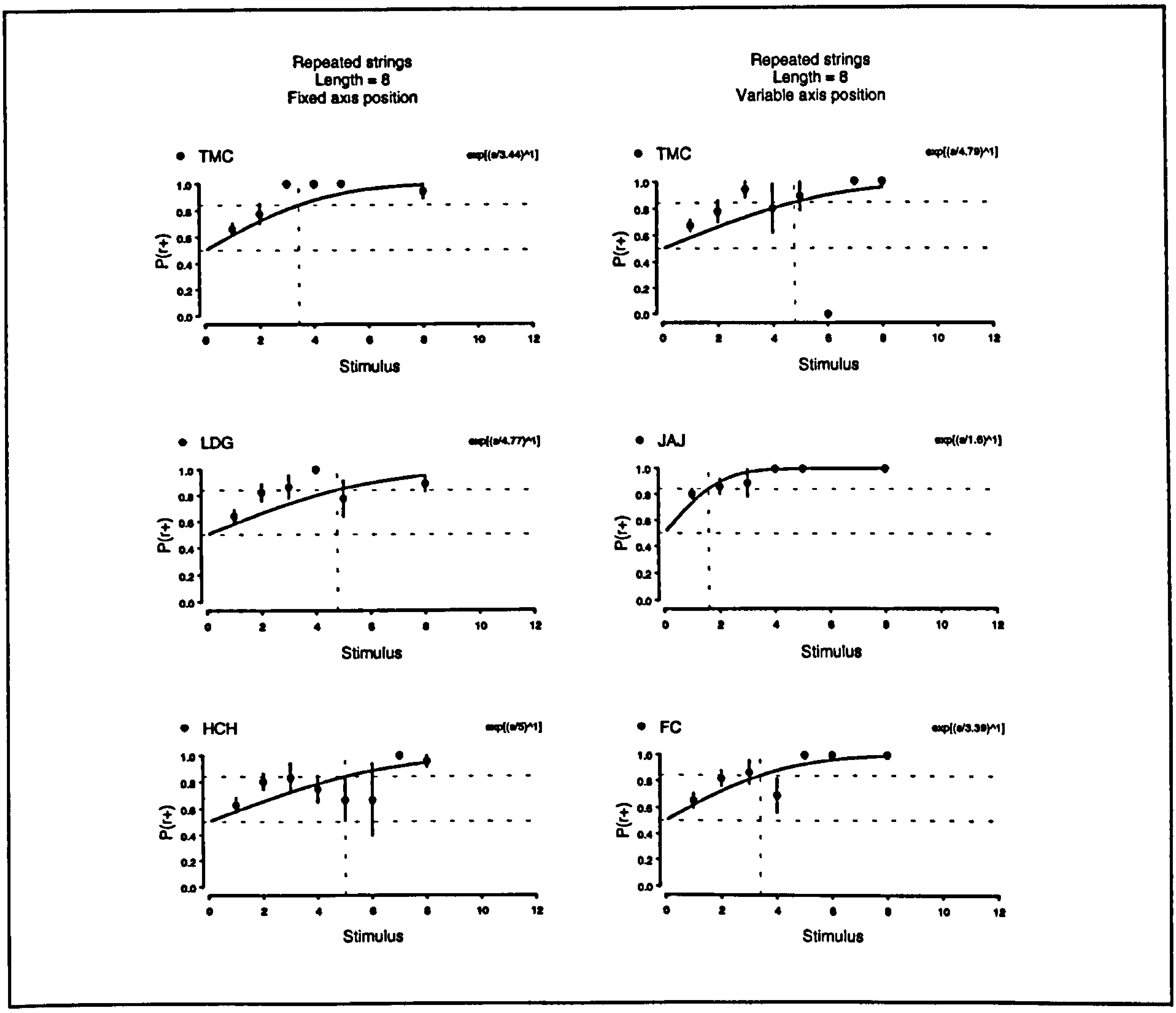

Figure E4. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

APPENDIX F

Shown here are the psychometric functions for Experiment 15 (strings of variable axis orientation). Functions for string length 2-8 are given here. Note that as string length increases, the data are presented on a smaller abscissa.

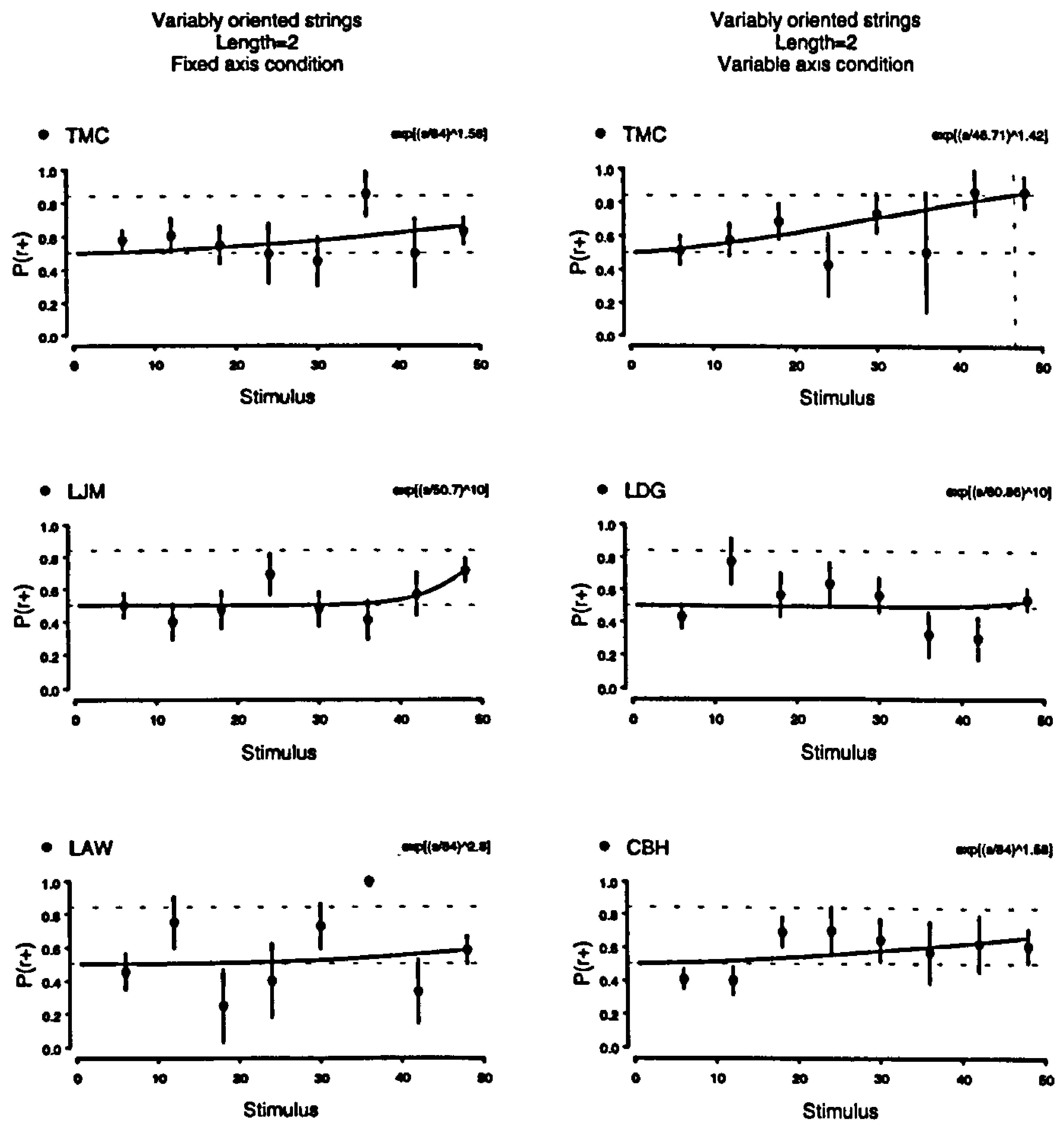

Figure F1. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

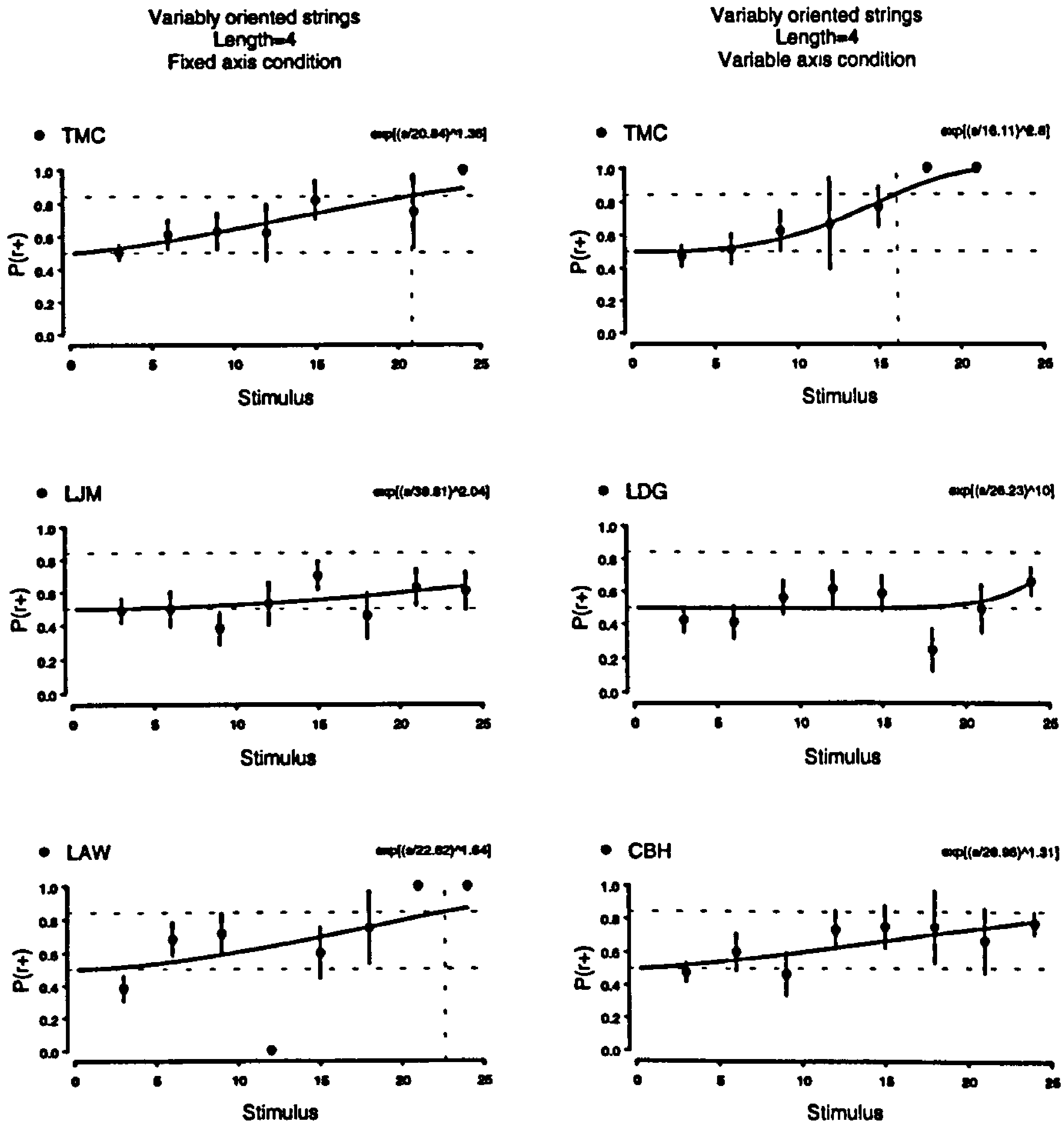

Figure F2. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

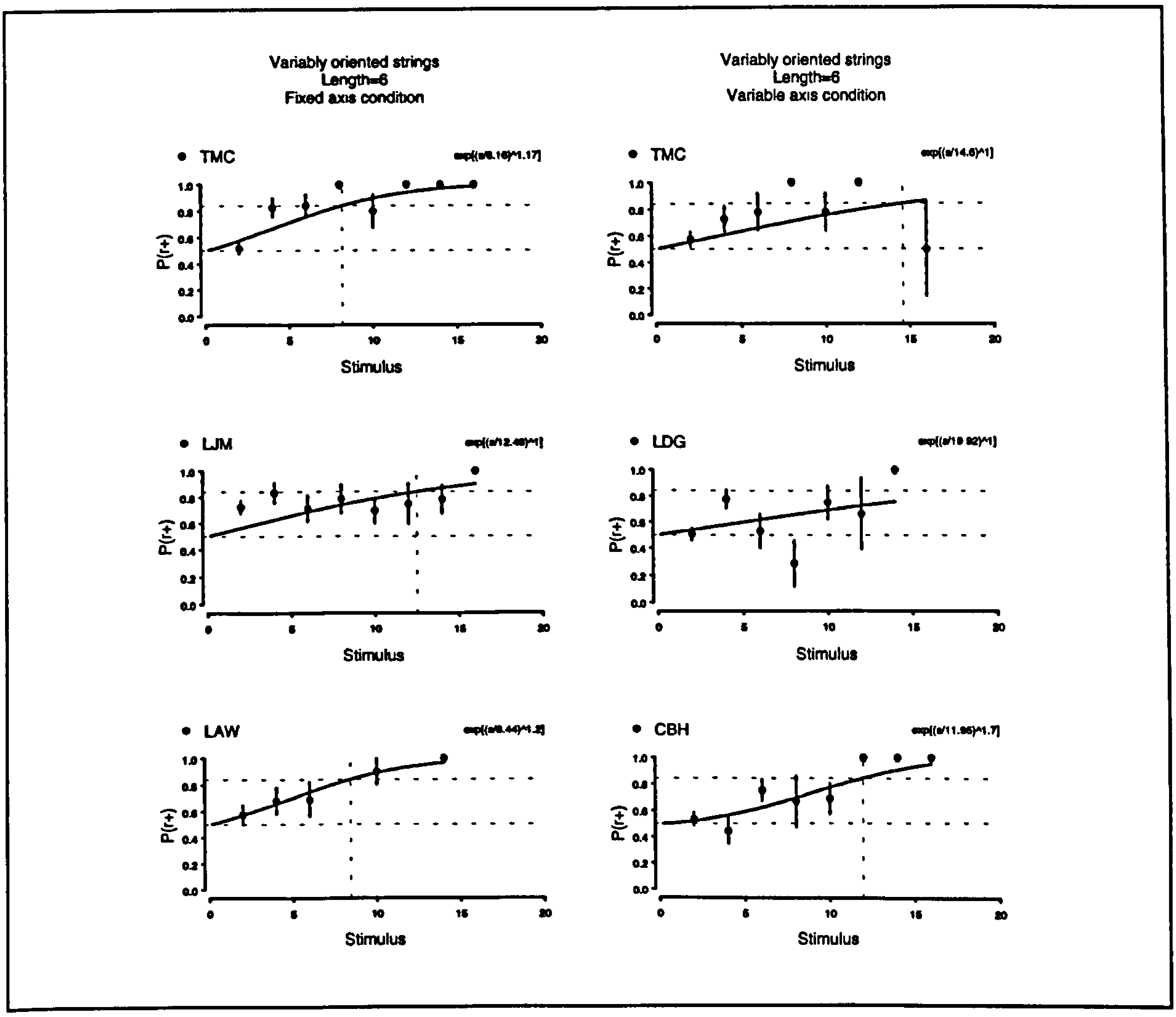

Figure F3. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.

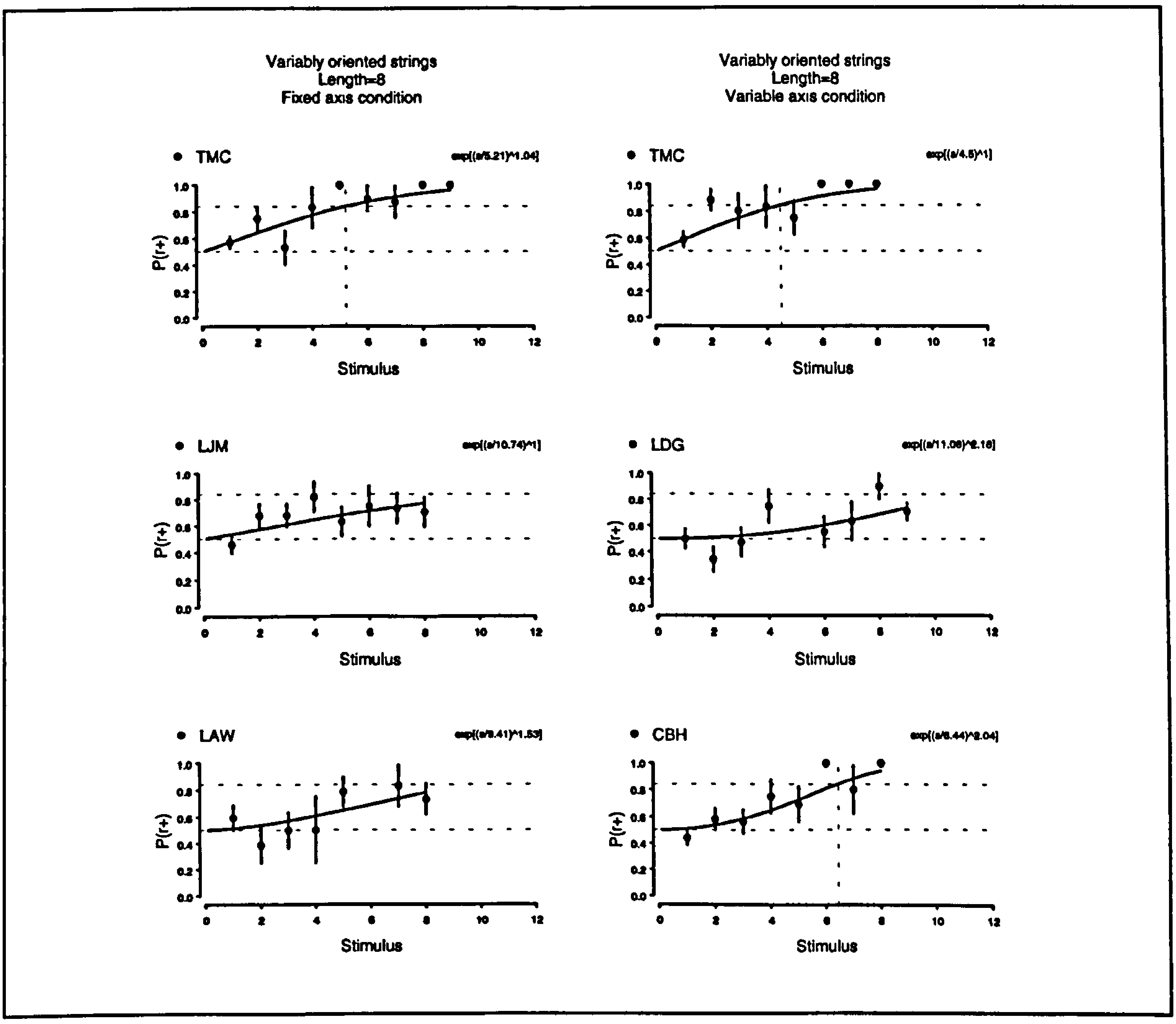

Figure F4. Psychometric functions of symmetry detection performance as a function of changing signal to noise ratio (SNR) for 3 subjects. The left hand column shows data from the fixed axis condition, the right hand column from the variable axis condition. The ordinate, P(r+), is the probability (P) of responding correctly (+) to the stimulus image containing the symmetric cue. Abscissa is the number of symmetric pairs present in the display containing the symmetric cue. Each data point is the mean of 3 runs. Each run contained 64 measurements of response across the psychometric function at the positions on the function given by the data points. The stimulus level corresponding to the 83% correct threshold is marked on each psychometric function by a vertical dotted line, and is also given in brackets at the right hand side of the psychometric function. The second figure in brackets is the exponent of the function. The horizontal dotted lines mark the 50 and 83% correct points on the function.