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The Absolute Efficiency of Perceptual Decisions [and Discussion]

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Phil. Trans. R. Soc. Lond. B 1980 **290**, 71-82
doi: 10.1098/rstb.1980.0083

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Phil. Trans. R. Soc. Lond. B **290**, 71–82 (1980)
Printed in Great Britain

The absolute efficiency of perceptual decisions

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Our perceptions of the world around us are stable and reliable. Is this because the mechanisms that yield them are crude and insensitive, and thus immune to false responses? Or is it because a statistical censor that blocks unreliable messages intervenes between the signals from our sense organs and our knowledge of them? This question can be answered by measuring the efficiency with which statistical information is utilized in perception. It is shown that mirror symmetry can be detected in displays of otherwise random dots with an efficiency of up to 50 %; thus the statistical mechanisms are not crude and insensitive, and this aspect of sensory physiology and psychology may deserve more attention.

One would like to investigate higher peceptual mechanisms with types of psychophysical experiment that are as rigorous as those that have been used for investigating colour vision, absolute thresholds or acuity, but a glance at papers and textbooks is enough to show that this is not usually done. I want to suggest in this paper that it can be done. For simple tasks the physical or photochemical limits are known, and quantitative measurements are largely guided by this knowledge. If we knew what limited perception, this might prove a similar guide; hence the first question to discuss is the nature of the limits to the perception of more abstract properties of visual images than those involved in sensitivity, resolution or colour matching.

WHAT LIMITS PERCEPTION?

The reasons for an instrumental system's failing to respond can be divided into two classes. In the first, the input causes no change at all in the output; the gain is insufficient or the pointer is jammed against its stop by too strong a return spring. In the second, a change is present at the output, but it cannot be measured, or even reliably detected, because it is small in comparison with the changes in the output that occur without any deliberately imposed change at the input of the type the system is supposed to measure. It is often assumed that perceptual failures belong to the first category because, when asked to make a difficult judgement, one is usually unaware of spurious perceptions that hinder the judgement. For instance, when deciding which of two hemifields is the brighter one does not, in a good photometer, see them as flickering in intensity, or non-homogeneous, so that at one moment and in one place one hemifield is brighter, at another moment and another place the other is brighter. The same often seems to be true of more complex perceptions. In judging collinearity of a vernier, or in recognizing the photograph of an acquaintance, one is not aware of a background of unstable misalignments or false facial resemblances from which the true impressions emerge; on the contrary, the true impression emerges in a secure way like a pointer rising from zero to a definitive reading. But I think that this common impression conceals the essential problem of perception, which is how reliable knowledge of the world around us is extracted from a mass of noisy and potentially misleading

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sensory messages. What I am suggesting is that the statistical step of extracting knowledge is often solved *before* we consciously perceive anything at all, and that is why our perceptions are usually reliable.

Let me give three prior reasons for believing that avoidance of spurious impressions is a major problem of perception, whether or not one is consciously aware of it. The first is simply that many psychophysicists would not agree with the description I gave in the previous paragraph of the way that weak perceptions arise. They would hold that spurious perceptions *do* occur, and that subjects can, if pressed, set their criterion for a particular perception at such a level that it will occur at almost any desired frequency in the total absence of the input signal. This is certaintly my own subjective experience at the absolute threshold of vision (Barlow 1956), and Sakitt (1972) has demonstrated clearly that subjects can be persuaded to respond to very few quantal absorptions, at the expense of the increase in the proportion of false responses that signal detection theory leads one to expect (see Swets 1964). Thus a closer investigation of the way that weak perceptions arise tends to support the view that perception failures belong to the second class and do not result simply from inadequate gain or high thresholds.

The second prior reason for emphasizing the importance of noise in perception is a general argument: sensory nerve fibres must under ordinary conditions be responding with complex patterns of activity at immensely variable rates, and it is hard to conceive of any mechanism testing the patterns of activity for the presence of a perceptual property that would be immune to spurious responses and entirely avoid false alarms, unless of course it was very insensitive. The problem is how to reach a conclusion from a mass of fragmentary information: our senses give us *knowledge* of the world around us, and one recalls Fisher's remark that new knowledge can *only* be created by statistical testing. It is certainly true that the best way of analysing the sensory messages would be to apply a battery of statistical tests to them, and some proposals along these lines will be made later.

One may also remark that psychologists are well aware of the importance of statistical tests when it comes to submitting a paper for publication in a reliable journal; it would be strange if they denied the importance of statistical tests of incoming messages when a sensory system is submitting them to higher levels of the nervous system.

A third reason for preferring the view that perception is often noise-limited is illustrated in figure 1. As the quality of the type deteriorates, it becomes more and more difficult to identify the middle letter: is this because the necessary information has sunk below the threshold of a needlessly insensitive perceptual mechanism, or is it because noise has been introduced? In figure 2 the same letters are shown at greater magnification, but in spite of this, perception fails at about the same point. Magnification fails to help, presumably because the noise is magnified with the signal. In this case we know that we fail to see the letters because the noise level has risen too high, but it does not seem subjectively very different from many other cases where perception fails, so it is natural to suspect that noise is important there too.

These three reasons for believing that sensory messages are statistically tested before we become aware of them make the idea plausible, but we need quantitative tests to become more fully convinced. The real question is whether the postulated statistics are done well, for it would be possible to regard any crude criterion for eliminating weak sensory messages as some kind of statistical method. Suppose, for instance, that one asks one's research assistant to fit a line to a set of points, and he simply joins the two extreme values; is that to be regarded as a statistical

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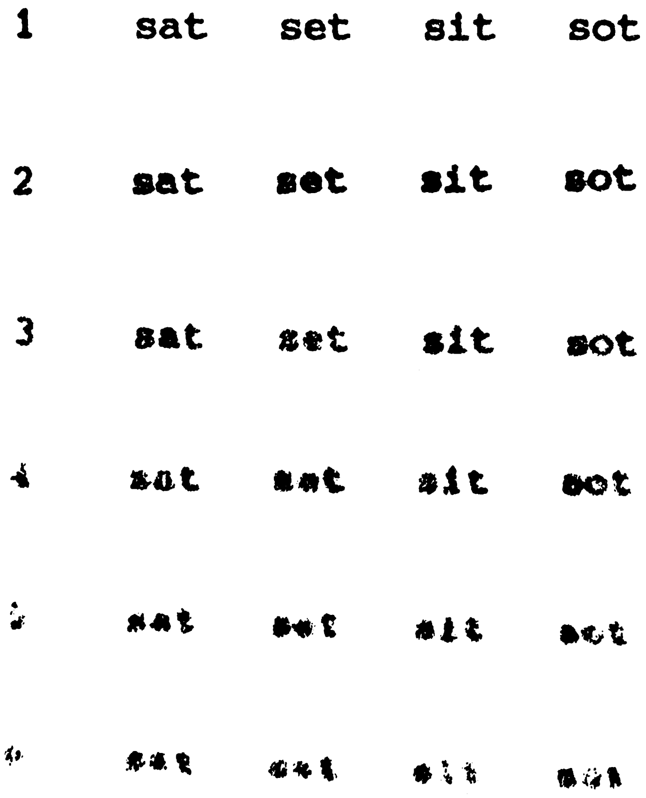

FIGURE 1. The quality of the print makes it difficult to distinguish the letters in lines 5 and 6.

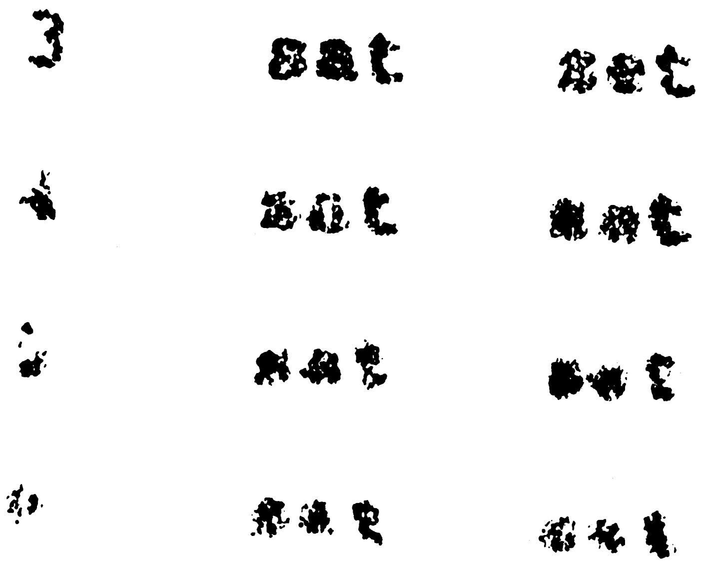

FIGURE 2. Magnification does not cure the problem of figure 1 because the noise is enlarged with the signal. Many perceptual limits are presumably set by noise, not by inadequate magnification or contrast.

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method? Maybe, but it certainly is not a good one, and what is implied by the hypothesis is that *good* statistics are used in sensory systems to eliminate spurious, ureliable perceptions. To test this, we must measure how well the statistics are performed. This was the motive for the experiments that I shall now describe. The question is an important one, for the statistical limitations of induction may be as important a guide to understanding higher perceptual processes as the physical limits of image formation and light absorption are to the earlier steps of vision.

CHOICE OF TASK

If you look at the three pairs of pictures in figure 3 you will agree, I think, that those on the left have a property in common with each other that enables them to be distinguished at once from those on the right. This property of bilateral symmetry is one that we can perceive very readily and directly, without conscious introspection to check whether a dot or small configuration on the left has its mate on the right. In this respect it is like simpler perceptions such as that of the colour of texture of a surface, or the collinearity of a row of dots, but it is a type of perception that seems to lead towards more complex tasks such as that of identifying a letter, or recognizing a face. For many of the simpler tasks, we have plausible ideas about the underlying phsyiology, but for symmetry I, at least, started out with no ideas at all about mechanism. But the detection of symmetry is a definite perceptual ability, and the characteristics of human performance at this task ought to give hints about the physiology, as has been the case with measurements of human sensitivity, acuity and colour vision.

Symmetry is also interesting because its detection is necessarily an associative process. If I cover up the right halves of each pattern in figure 3, there is nothing to tell which is symmetric; this can only be detected by comparing left and right halves, and this comparison may operate over the whole breadth of the pattern. Finally, symmetry is one of those 'Gestalt' processes which psychologists often employed 20 or 30 years ago to taunt and mystify innocent physiologists, and it would be extraordinarily gratifying to find a satisfactory explanation of its detection.

To summarize, the perception of symmetry in arrays of random dots as shown in figure 3 is a global, Gestalt, associative, process that is complicated enough to pose an interesting challenge, but simple enough for one to hope that psychophysics may throw light on the mechanism and what limits it.

METHODS

The first experiments, done with B. Reeves, explored the range of conditions under which symmetry could be detected in patterns of dots, but we wanted quantitative answers so we usually did the experiments as follows (a fuller account is to be found in Barlow & Reeves 1979). The subject sat at a keyboard facing an oscilloscope screen, with a computer programmed to generate examples of dot patterns according to one of two paradigms. The two paradigms might be those illustrated in figure 3, that is either 100 dots were positioned entirely at randon as on the right, or 50 dots were placed at random and 50 as pairs to the first 50 mirrored about the midline vertical. Initially the subject could obtain samples generated according to either paradigm at will, and from these he learned the perceptual characteristics of each population. When he had seen enough known samples, the computer generated 100 selected at random from the two populations, and the subject's task was to classify them. The

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correctness of each trial was signalled so that his knowledge of the two populations was continually refreshed. From the results, the proportion correct for each class was calculated and expressed as d'; this is the measure of detectability used in signal detection theory, and is best regarded for present purposes as an estimate of the signal:noise ratio of whatever quantity in the nervous system is used for making the distinction between symmetric and asymmetric patterns. In terms of this quantity it is the separation of the means of the two populations divided by their standard deviation (see Swets (1964) for further details).

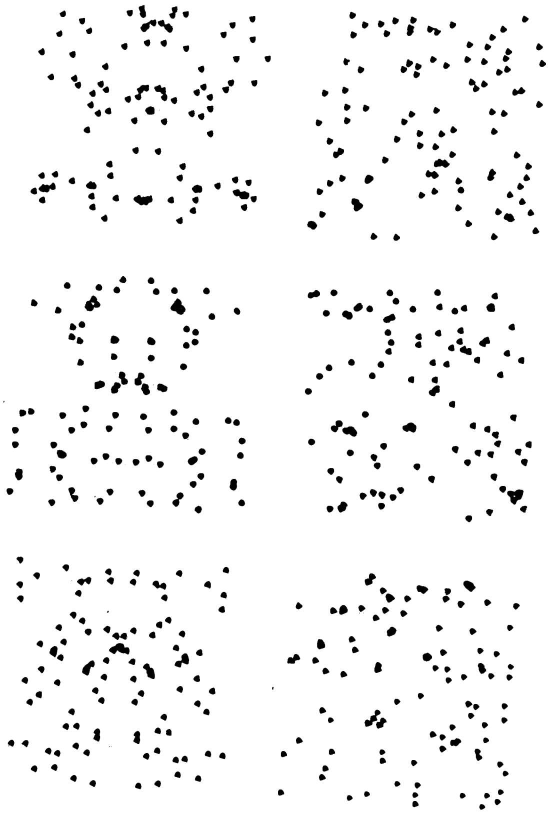

FIGURE 3. Examples of random patterns with mirror symmetry (left) and without mirror symmetry (right).

If the two populations shown in figure 3 had actually been used, a good subject would have made no errors; this corresponds to an infinite d', so the task must be made more difficult to ensure that the results lie within the range where the measure works properly. We have done this by arranging for only a proportion P of the dots to be in pairs, the remainder $(1 \times P)$ being placed at random over the whole pattern. With $P = 0.5$ or 0.8, enough errors are made for the d' to work satisfactorily.

RESULTS

Our first results showed that symmetry could be detected in brief exposures when the axis was not vertical (figure 4) and when it was displaced from the midline (figure 5), though both of these made the task harder. Clearly these results have important implications with regard to mechanism, for the task of detecting symmetry about the vertical midline of the visual field would have needed a much simpler and more stereotyped operation than what we now know is

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required. We also obtained evidence that the impression of symmetry could be graded over a considerable range and that the dots giving rise to it could lie some distance from the axis, not necessarily adjacent to it, thus confirming that it could not be performed by operations restricted to limited regions of the visual field.

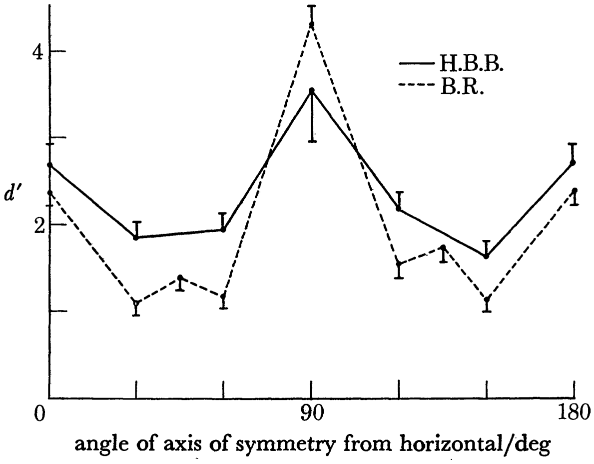

FIGURE 4. Effect of the orientation of the axis of symmetry: 100 dots in a circular field (4.2°) with a proportion 0.8 in symmetric pairs were to be discriminated from 100 randomly placed dots after an optional number of familiarizing trials. Exposure time was 100 ms and the axis was constant in each run of 100 trials. Discriminability is best with the axis vertical, but the task can be performed at other orientations. (From Barlow & Reeves (1979).)

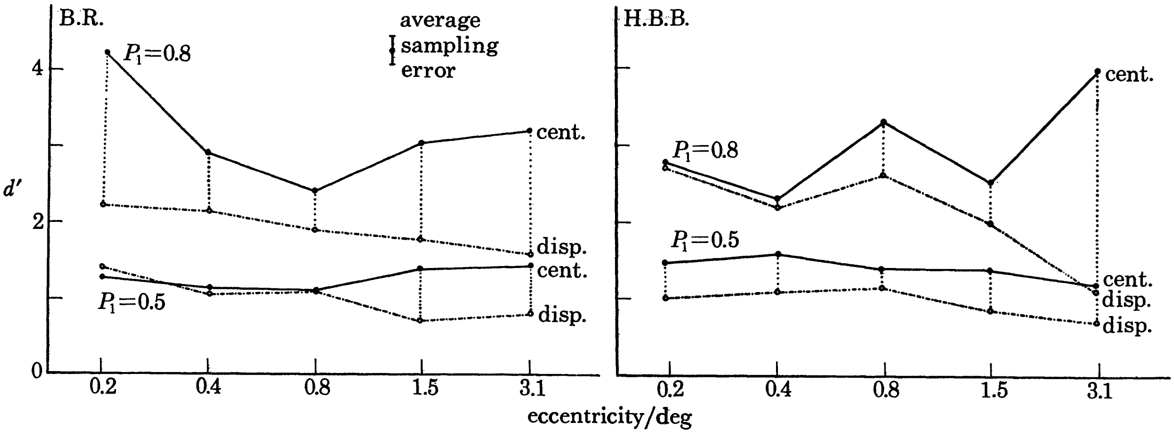

FIGURE 5. Effect of displacement of the axis of symmetry. The two subjects fixated a mark; shortly after its disappearance the figure appeared for 100 ms either centrally (marked cent.) or displaced at random either to the left or right (marked disp.) by the movement shown on the abscissa. In all but two cases performance was worse on the displaced patterns, but the task can still be done even with displacement up to 3°. (From Barlow & Reeves (1979).)

These experiments showed that the mechanism was versatile, but told us little about its nature. We therefore started to think of possible ways of distinguishing symmetric patterns like those on the left of figure 3 from asymmetric ones. We paid particular attention to the factors that would set a limit to its detection, for if we understood this we should be able to assess how good human performance was in absolute terms, and thus obtain evidence on the issue whether the statistical testing of sensory messages is important.

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For these computer-generated patterns we are in the strong position of knowing exactly the rules that generated them, and because of this we can also specify how best to detect them. Suppose, for example, that a list of the coordinates of the dots of a pattern in figure 3 is available. If the pattern is symmetric, the very first dot in the list will have a symmetric mate, and whether this is so can readily be found by searching through the coordinates of all other dots. Now a positive result of the search is not infallible evidence that the pattern belongs to the left-hand, symmetric, group, because a dot might, by coincidence, have been placed in the symmetric position even if all dots had been placed at random. The actual chance of this happening depends on the accuracy with which dots are positioned. In our system the accuracy both vertically and horizontally is normally 0.1% because we use 10 bit digital–analogue converters, and it will be seen that there is only a small chance that one of the 99 candidate-pair dots will be positioned in any of the 10^6 dot positions that would entitle it to be considered a pair to another dot.

The situation changes radically if the accuracy of placing the paired dots is less. For instance if the accuracy was only 10% in each direction, there would be only 100 distinct positions for a dot and there are very likely to be many dots positioned as pairs, even when every one is placed independently and at random. In this situation I do not think that one can do better than to count up the total number of qualifying pairs and use this count to decide whether a particular pattern is from the symmetric or non-symmetric population. It is clear, however, that when the accuracy of placing pairs is very poor the number of spurious pairs in totally random patterns will rise, and the variability in this number may obscure the difference between samples from symmetric and random populations. Corresponding to this limit to the discrimination of symmetric from random patterns from the coordinates of their dots, we may expect that the appearance of symmetry will vanish as the accuracy of placing the mirror dots is diminished. The question is, do the perceptual mechanisms do a good job in combating this possible factor limiting the detection of symmetry?

Figure 6 shows how reducing the accuracy of placing the symmetric dot impairs performance. The tolerance given on the abscissa scale indicates the range of positions within which the dot was placed, and it applied both vertically and horizontally. Thus for an angular tolerance range of 16′, the paired dot was placed at a random position in a square frame of side 16′ centred on the exactly symmetric position. It will be seen that performance drops off when the tolerance range is 8–16′, which is a surprisingly large figure compared with two point acuity of 1′ and the positional accuracy of 6″ or less attainable in a vernier task. Evidently symmetry detection does not depend upon a high-precision mechanism, but rather upon a low-resolution system.

The continuous line in figure 6 shows the performance predicted from counting the number of pairs that qualify as symmetrically placed for each tolerance range. For low tolerance ranges this can be calculated from simple geometric considerations, but the simple calculation is inaccurate at large tolerance ranges because the borders of the patterns spread out and the average dot density tapers off. This ideal curve was thus obtained by a computer simulation in which the coordinates were searched in the manner outlined previously. The ideal d′ is simply the difference between the mean numbers of qualifying pairs in the symmetric and unsymmetric patterns, divided by the standard deviation of the mean number.

For tolerance ranges above about 12′, the curve fits the points quite well, but note that the ordinate scale for the ideal curve is at the right, and the values are twice those on the left. Thus for moderate and large tolerances, the human subjects' d'_{E} is half the ideal d'_{I}. That corresponds

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to an efficiency of $\frac{1}{4}$ or 25%, because the ratio d'_E/d'_I must be squared if one wishes to express efficiency in the way that Fisher (1925) suggested. The figure then means that on average 25% of the information in a particular pattern is utilized in forming the decision as to which population it was derived from. I think that this is quite a high figure when one considers the nature of the task, and we started speculating on the type of mechanism that would achieve it.

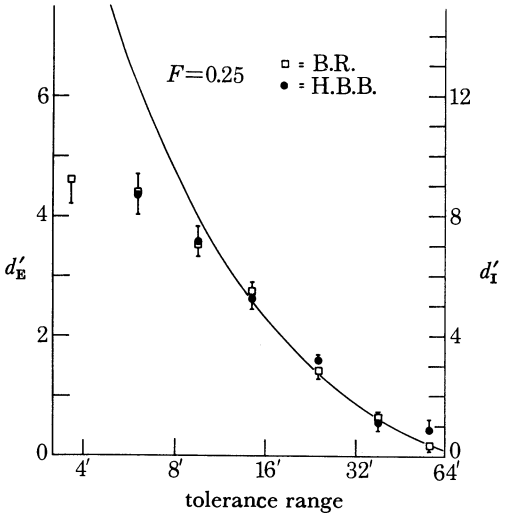

FIGURE 6. The accuracy of pairing was varied by placing the mirror pair to a dot at a random position in a square area centred on the true position and of side as given on abscissa. Ordinate shows d'_E for discriminating samples of the inaccurately paired population from a random population, with precautions taken to avoid other cues as to the origin of the sample. The continuous line shows the d'_I values obtained by counting the total number of pairs that would qualify as symmetric under the tolerance range being used, and basing the discrimination on this number in a computer simulation of the experiment. The scale for d'_E is at the right, and is twice the left-hand scale. For tolerances greater than about 12′, the points fit the curve. This means that the subjects used 25% of the statistical information in the patterns. (From Barlow & Reeves (1979).)

In the ideal method, every possible pair of dots was inspected to see if it qualified as a symmetric pair with the tolerance range in use. With 100 dots there are 4950 pairs, and it is hard to imagine a neural mechanism capable of conducting this search in the brief time required to detect symmetry, especially as the required pairing is determined by the position of the dots, not by positions in the visual field. Taking a hint from the fact that the system tolerates a good deal of inaccuracy in the placing of symmetric pairs, our first attempt to formulate a simpler model postulated comparisons of the numbers of dots falling in fixed areas of the visual field. Figure7 shows the scheme. The 2° square within which the dots fall is divided up into sixteen $\frac{1}{2}° \times \frac{1}{2}°$ squares, and the numbers in mirror-paired areas are compared as indicated. A computer simulation of this model was run, and the results are shown in figure 8. The agreement was almost embarrassingly good, and (with K. Mullen) we started to do some other tests of the model.

If performance depended only on the numbers of dots in the squares shown in figure 7, it should drop to zero if the symmetric patterns were constrained to have equal numbers in each of the subsquares. There would still be evidence of symmetry in the detailed pattern within the subsquares, for this could be mirrored or not in the corresponding subsquare, but according to the model only the number in a subsquare is used and these were constrained to be all equal. The result was disappointing. Performance was only slightly impaired compared with the

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usual paradigm for producing patterns, so removing the only evidence used by the model had little influence on human performance.

Next we tried generating patterns in the usual way, but perturbing the arrangement of the dots within each subsquare by a re-randomizing process, leaving the number in each subsquare unchanged. The model says that performance is uninfluenced by the detailed arrangement of the dots in these squares and should be equally good if their positions were re-randomized. This, however, had a devastating effect on performance, efficiency dropping to only 1 or 2 %. We then thought that we might be able to avoid the additional noise caused by re-randomization by replacing all the dots in the square by a single square at the centre whose brightness or size was proportional to the number in the square. This was better, but the best efficiency was still no higher than 10 %. We therefore decided to test the essential features of our model separately.

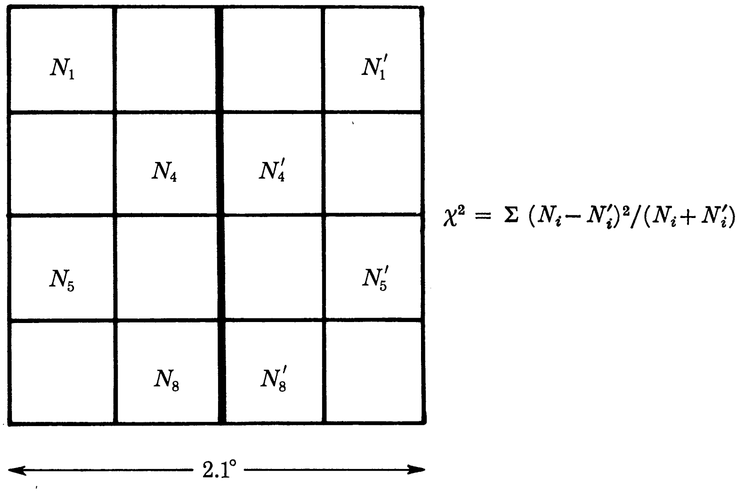

Figure 7. Model based on the idea that the human symmetry system counts the numbers of dots in large, fixed, areas rather than searching through all pairs, and bases discrimination on a χ^2 test performed on these numbers. It tests the hypothesis 'the numbers of dots are randomly divided between symmetric areas', and low values of χ^2 indicate symmetry.

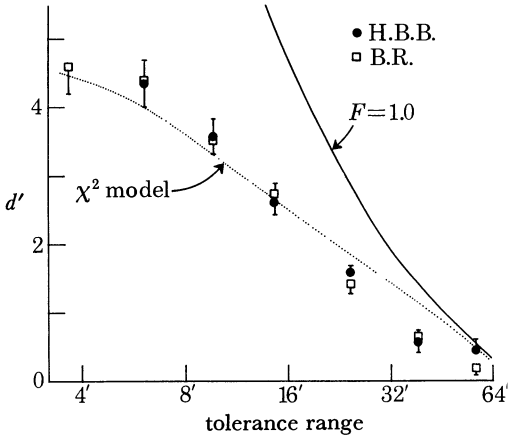

Figure 8. The performance of the model of figure 7 obtained by computer simulation is compared with the data points of figure 6. The model appears to fit well, and thus could account for human performance, were it not for other results described in the text.

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It is clear that many of the features are not only inessential but wrong. For instance, the model says that the areas that are compared between one side and the other across the mirror axis are square and do not overlap. The essential feature is that they are large, and at fixed positions in the visual field, not aligned on points of the image such as dot positions, because it is the large size and fixed position that greatly reduces the number of comparisons that must be made to assess whether symmetry is present. We were led to postulate this by the high tolerance or low accuracy of the symmetry mechanism indicated by the result of figure 6, and we therefore decided to test directly the idea that only a low-resolution system was required.

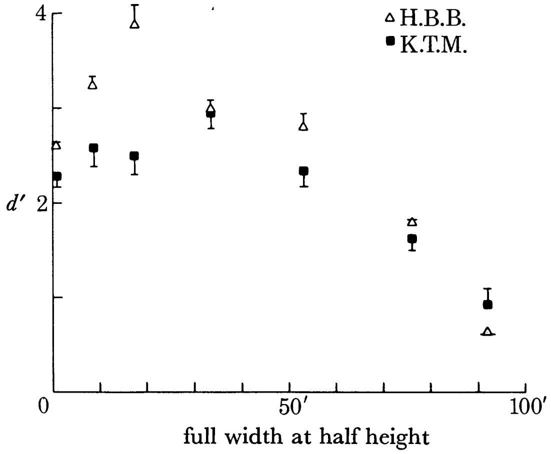

Figure 9. Patterns generated with a tolerance range of 15′ both vertically and horizontally were viewed through a diffuser placed in front of the oscilloscope screen. Ability to discriminate symmetric from random patterns was was only impaired seriously when the diffuser was at such a distance that the line spread function (abscissa) had a full width greater than 40′ at half height. This confirms that a low resolution system is involved in symmetry detection. However, it was not predicted that performance with moderate blurring would actually be better than with less blurring or none at all.

If that was the case, then blurring the dot patterns should have little effect on performance, for this would only cut out the high spatial frequencies that our model said were not used anyway. We set out to do this by placing a diffusing screen between the dot patterns and the viewer. By changing its distance from the screen the amount of high frequency reduction would be varied, and figure 9 shows the effect of doing this.

The abscissa gives the full width of the line spread function at half its peak height for a particular distance of the diffusing screen, and the ordinate gives the experimental value of d' obtained. As expected on almost any model, performance is impaired for large amounts of blurring, and as predicted by our model it is not impaired until the blur reaches $\frac{1}{4}$–$\frac{1}{2}$°. What was unexpected was that blurring actually improved performance up to a certain point: subjects do better at detecting symmetry when high spatial frequencies are eliminated. What this means with regard to the mechanism is not yet clear; one interpretation would be that the inaccurate positioning of mirror pairs introduces details on one side that are not mirrored on the other, and eliminating this detailed evidence for asymmetry by blurring makes it easier to detect symmetry in the coarse positioning of the dots. More thought will be needed to repair our battered model, and more experiments will be required to test the possibilities, but there is one implication with regard to the main purpose of these experiments.

Blurring the picture by interposing the screen removes information contained in high spatial

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frequencies and cannot make the task of detecting symmetry objectively easier. That is to say, it cannot improve the best attainable value of d'_{I}. So filtering out the high spatial frequencies must actually improve the efficiency of detecting symmetry.

Figure 10 shows a series of measurements with variable tolerance for placing the dots (cf. figure 6) with the diffusing screen at a distance that gave a line spread function of 25′ full width at half height; this corresponds to 50% attenuation at 0.76 cycle/deg in the modulation transfer function. The continuous curve gives ideal performance at an efficiency of 50%, and is a reasonable fit to the determinations made with tolerances down to about 10′. That is as high a figure as we have found for the performance of *any* psychophysical task, even ones in which much simpler judgements are made (Barlow 1978). There is not even any evidence that a simple threshold determinations, in which the subject does no more than decide whether a stimulus was presented or not, can be done any better, as I have argued elsewhere (Barlow 1977).

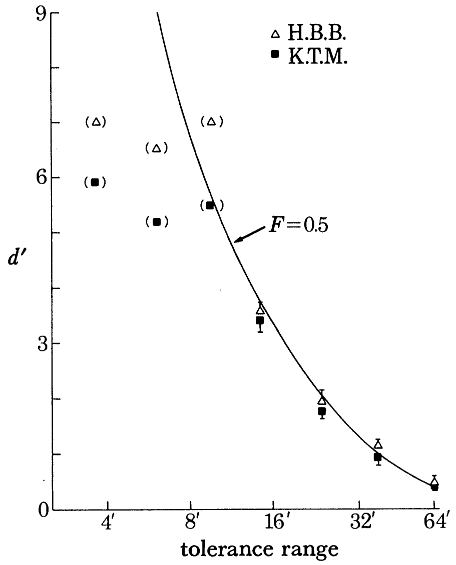

FIGURE 10. Performance with various tolerance ranges for symmetry production (cf. figure 6) when a diffusing screen is placed to produce a line spread of 25′ full width at half height. The continuous line represents utilization of 50% of the statistical information as to symmetry (see text). (Bracketed points are unreliable since subjects scored 100% correct on some of the trials.)

Detecting symmetry may not be a difficult task compared with recognition of a letter or a face, but it certainly has greater complexity than simply detecting the presence or absence of a specific type of signal; the difference, to my way of thinking, is similar to that between a χ^2 test for the adequacy of a hypothesis and the simplest of all statistical tests, that of deciding whether a sample belongs to a population of known parameters. The fact that the test of a more complex perceptual hypothesis, 'This pattern is symmetric', can be done with an efficiency of 50% shows that the limits to perception are often close to the statistical limits of induction. I think that the possibility that there is a statistical censor screening the messages from one's sense organs must make one take a new look at the anatomical structures and physiological mechanisms of sensory pathways, and perhaps also at the general psychological problems of perception.

I wish to thank B. Reeves, P. Mowforth and K. Mullen for their great help in these experiments.

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Discussion

S. LAL (*Department of Physiology, Chelsea College, Manresa Road, London SW3 6LX, U.K.*). I should like to ask two questions. First, what kinds of statistical decision tests are being used by neural systems in detecting variations of image dot intensity, mirror symmetry, etc.? Secondly, what proportion of the false responses made can be ascribed to biased hypothesizing as compared with stimulus ambiguity or distorted measurement?

Neural systems cannot be simple-minded relative frequency theorists. For there would be obvious disadvantages for a species in calculating the long-term relative frequency odds that an object approaching was a lamb rather than a lion. In other words, decisions could not be made (or rather would be unlikely to be made) on the basis of repeated trials.

As to the problems of false responses, they could be due to biased hypothesizing by the neural detection–decision elements rather than to stimulus uncertainty or distorted measurement. Presumably one could test for these rival explanations by setting up detection tasks that involved the resolution of stimulus ambiguity or that used biased measurements.

H. B. BARLOW, F.R.S. Presumably the visual mechanism incorporates assumptions about the type of the distributions that it is called upon to handle, and it is only the parameters of the assumed distributions that it estimates from the nature of the messages received. I do not know what these assumptions are, and it is difficult to see how one might find out, for the kind of measurements that one can readily make yield estimates of barely sufficient accuracy even when aimed at means and variances. Much work would be involved in estimating skewness or kurtosis, but it is certainly worth while bearing in mind the possibility that a mismatch between the distribution assumed, and that which actually occurs, might be responsible for certain visual illusions or errors. Perhaps there are perceptual analogies to the errors of judgement that people frequently make when asked to guess the expectation of two or more members of a small group having the same birthday.

With regard to false responses, I am not sure that the distinction that is suggested is helpful, either in theory or practice. The psychophysical method that I use is very simple from the point of view of statistical decision theory, for all I ask the subject to do is select one of two 'hypotheses' on the basis of 'results'. The results are the pattern he has just seen, and the hypotheses are that this came from one or the other of two populations which I assume he knows all about. The method requires that the subject makes errors of both kinds – he must wrongly assign samples to both populations – and it works best when they are about equally frequent and around 10%. These restrictions are good from the point of view that they sharpen the probe with which I am testing the system, but the answer to the question raised would, I think, show up rather indirectly, as inefficiencies of performance under certain test conditions.