The Arrangement of Bristles in *Drosophila*

by J. Maynard Smith and K. C. Sondhi

From the Department of Zoology and Comparative Anatomy, University College, London

INTRODUCTION

Much of the geometrical complexity of animals and plants arises by the repetition of similar structures, often in a pattern which is constant for a species. In an earlier paper (Maynard Smith, 1960) some of the mechanisms whereby a constant number of structures in a linear series might arise were discussed. In this paper an attempt is made to extend the argument to cases where such structures are arranged in two-dimensional patterns on a surface, using the arrangement of bristles in *Drosophila* as illustrative material.

The bristles of *Drosophila* fall into two main classes, the microchaetes and the macrochaetes. A bristle of either type, together with its associated sensory nerve-cell, arises by the division of a single hypodermal cell. The macrochaetes are larger, and constant in number and position in a species, and in most cases throughout the family Drosophilidae. The microchaetes are smaller and more numerous, and show no fixed number or pattern in a species, although they do show some regularity in spacing. A number of mutants are known which alter the number and arrangement of the macrochaetes, usually by eliminating one or more pairs.

An explanation is put forward of the variations in the number and arrangement of the microchaetes, and of the macrochaetes in some mutant stocks, in terms of a common morphogenetic model. This model is an extension of that suggested by Stern (1956) in the light of mathematical considerations due to Turing (1952). It is hoped that this model may have some relevance to the arrangement of other repeated structures.

PREPATTERN AND COMPETENCE

Stern (1956) has analysed a number of bristle patterns in *Drosophila* by means of genetic mosaics. In the mutant achaete, which removes the posterior pair of dorsocentral bristles on the thorax, he showed that if in a predominantly wild-type fly a patch of genetically achaete tissue covered the site of the bristle, no bristle was formed; but if in a predominantly achaete fly the site of the bristle was covered by genetically wild-type tissue, a bristle was formed. He suggested

---

1 This paper is dedicated to Professor L. C. Dunn in recognition of his long and distinguished career.

2 Authors' address: Department of Zoology, University College, Gower Street, London, W.C. 1, U.K.

that the presence of a bristle required the existence of a 'prepattern' determining its position, and the existence of cells competent to respond to the prepattern by forming a bristle. The normal prepattern exists both in wild-type and in achaete flies, but genetically achaete cells are incompetent to respond to this prepattern. An essentially similar conclusion was reached by Maynard Smith & Sondhi (1960) from a study of populations of D. subobscura homozygous for the mutant ocelli-less, which were selected for different expressions of the mutant.

The prepattern is most easily pictured as the distribution of an inducing substance with regions of high and low concentration, the regions of high concentration occurring at sites where bristles later form. A process whereby such a distribution could arise has been suggested by Turing (1952). He considered the distribution in a morphogenetic field of two chemical substances, or 'morphogens', together with an adequate supply of substrate from which they could be synthesized. These morphogens are free to diffuse and to react with each other. He showed that for certain values of the rates of reaction and diffusion the initial homogeneous equilibrium was unstable; any disturbance of the equilibrium, for example by Brownian movement, leads to the development of a standing wave of concentration of the morphogens. The actual pattern of peaks and valleys of concentration depends on the size and shape of the field, and on the 'chemical wavelength', i.e. the preferred spacing between peaks, which in turn depends on the rates of reaction and diffusion; it does not depend on the nature of the initial disturbance.

This provides a simple model of the process whereby a prepattern could arise. In cases in which a pattern is constant throughout a species, it is a more satisfactory one than Wigglesworth's competitive model (1959). According to Wigglesworth's model, the positions of the bristles will depend in part on which particular hypodermal cells happen by chance to be the first to differentiate, whereas Turing's mechanism would give rise to a pattern independent of the initial chance disturbance. Thus a competitive mechanism could explain the arrangement of a series of structures whose only regularity is the approximately equal spacing between them, but not of structures whose arrangement is constant from individual to individual.

The way in which the arrangement of structures may depend on the shape of the field as a whole has been shown by Sengel's (1958) work on the development of feather papillae on the skin of the chick in vitro. If skin is removed from the dorsal region of the embryo when the feather rudiments have just become visible, these rudiments disappear, and later new feather papillae develop in different positions, the first to appear forming a row along the centre of the explant.

Turing's two-morphogen model is, however, too simple to explain all the facts. As Waddington has pointed out (1956), it would predict that different patterns would arise if particular stages of differentiation occurred in embryos of different sizes, and this is not always the case. But in spite of this and other difficulties,
Turing's suggestion of how a prepattern might arise is probably along the right lines.

**THE ARRANGEMENT OF MICROCHAETES**

For reasons of economy, it would be desirable to explain the arrangement of microchaetes and of macrochaetes by similar mechanisms, differing only in the accuracy with which they are regulated. Fortunately, there is some observational evidence that similar mechanisms are involved. In this section it will be shown that the arrangement of microchaetes does show traces of the kind of regularity to be expected if their positions depend on the shape of the field as a whole; in the next section it will be shown that at least some abnormalities of macrochaete arrangement are of the kind to be expected from variations of a prepattern arising in the way suggested by Turing.

Text-figs. 1a, b show two solutions of Turing's equations in a uniform rectangular field, the dots corresponding to peaks of concentration of one of the morphogens; the solutions differ only because slightly different reaction rates have been assumed. Text-figs. 1c, d, e show the arrangement of microchaetes on the sternites of the 4th abdominal segment of three individuals of *D. subobscura*. The first shows a somewhat irregular pattern, the second shows clear rows of bristles parallel to the boundaries of the sternite, and the third shows diagonal rows. The resemblance between the two latter sternites and the theoretical distributions is obvious. Sternites with these regular patterns are quite common in flies with low numbers of bristles, but irregular arrangements
are more usual in flies with larger numbers of bristles. Even an occasional sternite of the type shown in Text-fig. 1 is sufficient to show that the pattern depends on the field as a whole, and such sternites are by no means uncommon.

MACROCHAETES

Text-fig. 2 shows the arrangement of macrochaetes and ocelli on the top of the head of Drosophila. The sex-linked recessive mutant ocelli-less in D. subobscura removes most of these structures. There is however, considerable variation in populations homozygous for the mutant, and by selective breeding for

![Text-fig. 2](image)

**TEXT-FIG. 2.** The arrangement of bristles and ocelli in D. subobscura in a, the wild-type, and b, c₁, c₂, individuals homozygous for the mutant ocelli-less. In the diagrams on the left, the curved lines represent the prepattern, pictured as a varying concentration of an inducing substance; the hatched areas represent the concentration of precursor; the upper horizontal lines represent the threshold level which the prepattern must reach if it is to induce a structure.
individuals with a larger or smaller number of structures, or with only particular structures present, a wide range of phenotypes, including the wild-type, have been obtained. These experiments have been described elsewhere (Maynard Smith & Sondhi, 1960; Sondhi, 1961 a, b, c). It has been shown that most of the results can be explained if it is assumed that there is an unvarying prepattern determining the positions of ocelli and bristles, and a varying amount of a common 'precursor' of ocelli and bristles. The absence of structures in unselected mutant stocks is due to the small amount of this precursor, but selection can both increase the amount of precursor, and also concentrate it in particular regions of the head. In this explanation the concept of 'amount of precursor' corresponds to Stern's concept of level of competence.

But, in addition to individuals lacking particular structures, we have also

![Diagram](image)

**TEXT-FIG. 3.** The arrangement of bristles and ocelli in *D. subobscura* in *a*, the wild-type, and *d, e*, individuals homozygous for the mutant ocelli-less. See legend to Text-fig. 2.
obtained individuals with various other abnormal phenotypes. It will now be shown that these phenotypes can also be explained in terms of the prepattern-precursor model. Reference will be made to the populations in which these phenotypes occur only when this is helpful in explaining their origin during development.

Text-figs. 2, 3, 4 show the various possible ways in which abnormal phenotypes can arise, and examples of phenotypes thought to have arisen in these ways. Text-figs. 2, 3 show changes arising from differences in the amount and

Text-fig. 4. The arrangement of bristles and ocelli in D. subobscura in a, the wild-type, and f, g, h, individuals homozygous for the mutant ocelli-less. See legend to Text-fig. 2.
distribution of precursor, and Text-fig. 4 changes arising from alterations in the prepattern. The various possibilities are as follows.

**Absence of structures**, due to a low level of precursor (Text-fig. 2b). These are the typical abnormalities in unselected ocelli-less populations. Text-fig. 2b shows the commonest phenotype in a population which had been selected so as to concentrate the precursor in the posterior region of the head and to remove it from the anterior region.

**Repetition of structures** (Text-fig. 2c). If the amount of precursor is greater than in the wild-type, it is possible that two structures should develop in response to a single peak of the prepattern. Text-figs. 2c, 2d show repetition of bristles and of ocelli respectively. Such repetition occurs mainly in populations which have been selected for an increased number of structures, and therefore presumably for an increased amount of precursor.

**Neomorphs** (Text-fig. 3D). If there can exist in mutant flies peaks of the prepattern to which genetically mutant tissue is incompetent to respond, it is possible that there also exist ‘submerged’ peaks of the prepattern to which wild-type tissue does not respond. If so, bristles might appear at the sites of these submerged peaks in mutant populations selected for increased competence. Text-fig. 3d shows a phenotype thought to arise in this way. The new bristle occurs in about 5 per cent. of flies in a population which has been selected for many generations for an increased number of structures. It is confined to this population, and occurs only in individuals in which all the normal structures are present. The bristle is constant in its position and orientation, and closely resembles in these respects a bristle which occurs typically in flies of a related family (Sondhi, 1961c). The main reason for thinking that it arises by the process shown in Text-fig. 3d, and not from a change in the prepattern, is that its presence is not associated with any change in the positions of other bristles.

**Displacement** (Text-fig. 3E). If the precursor is absent at the peak of the prepattern, but present a short distance away, it is possible that a bristle would develop in a position slightly displaced from the normal. Stern (1956) has plausibly interpreted cases of displacement in his material in this way, but we cannot in our material always distinguish displacements arising in this way from those due to a distortion of the prepattern. This difficulty arises if a bristle is displaced without any associated displacement of neighbouring structures. This happens most commonly in the case of the postvertical bristles, particularly in populations selected for a low number of structures. The base of the bristle is displaced posteriorly and medially, and the displaced bristle is directed in an antero-medial direction (Text-fig. 3e). Such displacements could be due to either of the mechanisms shown in Text-fig. 3e or 4f, although in the case of the postverticals the latter seems the more likely explanation, since the displacement is almost always in the same direction.

**Homeomorphic distortion**, i.e. a prepattern with the same number of peaks, but of a different shape (Text-fig. 4f). Text-fig. 4f shows a phenotype thought to
arise in this way; it is common in populations selected for a low number of structures on the centre of the head. The displacement of a single bristle could also be due to the mechanism shown in Text-fig. 3e above, but in these flies all three orbital bristles are displaced posteriorly, and this could happen only if the prepattern itself is distorted.

Non-homeomorphic distortion, i.e. a prepattern with a different number of peaks from the wild-type (Text-fig. 4G). Text-fig. 4g shows a phenotype thought to arise in this way; it also is common in populations selected for a low number of structures on the centre of the head. Four orbital bristles are present instead of three, and usually only the most anterior one is exactly in the position occupied by a bristle in the wild-type. The four bristles are evenly spaced; we have never observed the repetition of an orbital bristle, comparable to the repetition of a vertical bristle shown in Text-fig. 2 q. The interest of this particular phenotype is that it shows an unusual change in the arrangement of the macrochaetes, but one which arises by a mechanism which we believe to be that typically responsible for variations in the arrangement of microchaetes. In terms of Turing's model, the ratio between the chemical wavelength and the size of the field in which the waves are developing can vary within certain limits without involving any change in the actual pattern formed; but ultimately a threshold would be reached, involving the appearance of an additional bristle or bristles, and a respacing of other bristles in the field.

These mechanisms account satisfactorily for all the common abnormalities observed in ocelli-less populations. But occasionally there occur additional ocelli or bristles, at sites which are not occupied by such structures in the wild-type, and which vary from individual to individual in an irregular manner. Text-fig. 4h shows such an additional ocellus. Additional ocelli and bristles of this sporadic type occur in populations selected for a high number of structures, with frequencies of about 0.9 per cent. and 0.6 per cent. respectively.

There is one unexpected feature of these results. It appears that a mutant, which was at first thought to affect only the amount and distribution of the precursor, also, although less commonly, modifies the prepattern, since the phenotypes in Text-fig. 4f, g cannot easily be explained without this assumption. The mutant is therefore pleiotropic, in that it modifies two separate morphogenetic processes. But it seems plausible to suggest that the primary effect of the gene is to alter the concentration of precursor, and that this in turn may, in extreme cases, modify the development of the prepattern.

**DISCUSSION**

The development of specific structures at specific sites in *Drosophila* has been regarded as the result of two processes, one concerned with the formation of a prepattern which determines the positions at which structures are formed, and the other responsible for the competence of cells to respond to this prepattern by forming the appropriate structures. The justification of this division is that
the two processes can vary independently of one another. Our strongest evidence for thinking that the competence can vary while the prepattern remains unchanged comes from an ocelli-less population in which individuals were chosen as parents if they had the two posterior ocelli but lacked the anterior one (Maynard Smith & Sondhi, 1960). In this population the frequency of the selected phenotype increased from 15 to 64 per cent. At the same time, the frequency of individuals possessing the ocellar bristles, which lie close to the anterior ocellus, decreased almost to zero. In those individuals which did possess the anterior ocellus, the ocellus was not displaced posteriorly, but was usually much smaller than in the wild-type. These results only make sense if it is supposed that the prepattern determining the position of the anterior ocellus was unaffected by selection, and that the population changed because the competence of the cells to respond was reduced in the anterior part of the head. In contrast, our strongest reason for thinking that the prepattern can change are the phenotypes shown in Text-fig. 4f, g.

The distinction between prepattern and competence is therefore made necessary by the nature of the variation observed. Variations in adult structure do not necessarily, or even usually, reflect changes in prepatterns. Differences between individuals may arise because of genetically determined differences in competence between their cells. The importance of this distinction has been increased by the work of Kroeger (1958) on the wing-hinges of *Ephestia*. He has been able to show that differences between serially homologous parts of the same individual may have a similar origin, in different responses of cells to identical prepatterns, although in this case the differences in response are not genetically determined, but arise in the course of embryonic differentiation. However, these successes in explaining variation in adult structure in terms of varying responses to unchanging prepatterns carry with them the danger that prepatterns may come to be regarded in a somewhat mystical light. It is therefore an important feature of the ocelli-less mutant that some of the abnormalities to which it gives rise can only be interpreted as the results of changes in the prepattern.

One question which it was hoped that this investigation would answer is whether the developmental mechanisms responsible for patterns which are constant in almost all members of a species have anything in common with those responsible for patterns which vary from individual to individual. The kinds of variation in the arrangements of microchaetes and of macrochaetes which have been described support the idea that the processes which determine the positions of the two types of bristle are similar. If so, the relative constancy of macrochaete patterns presumably arises because the number of macrochaetes in any particular pattern is small. It has been argued at length elsewhere (Maynard Smith, 1960) that mechanisms formally similar to that suggested by Turing can give rise to a constant pattern only if the number of peaks is small (approximately 5 to 7). The essence of the argument is that the number of
structures formed will be the nearest integer to the ratio of the size of the field
to the ‘chemical wavelength’; consequently the larger the number of structures
which is to be kept constant, the smaller must be the coefficient of variation of
this ratio. The simplest method of ensuring the constancy of larger numbers is
by a process which was called ‘multiplication’. The morphogenetic field is first
divided by one patterning process into a small number of large regions, and then
subdivided by a second process into a larger number of smaller regions. It is
therefore interesting that Ursprung (1959) has shown that the development of
the genital imaginal disks of *Drosophila* has a stepwise character of this kind.
In more general terms, one reason for the stepwise nature of so many develop-
mental processes may be that only processes of such a kind can give rise to
uniform results.

If a number of structures are arranged in a linear series, as are for example a
series of segments, a multiplicative process requires that two patterning processes
be separated in time, occurring one after the other. But if the structures are
arranged on a surface, another type of multiplicative process is possible, with
an equivalent gain in accuracy. Two patterning processes can occur simulta-
neously, but along different axes; one process can determine the number of
‘rows’ and a second the number of structures in each row. This requires that the
morphogenetic field should be initially anisotropic, whereas Turing supposed
the field to be isotropic. It is therefore interesting that Weiss (1959) has shown
that the regular arrangement of fish-scales depends on a pre-existing anisotropy;
i.e. on the presence of two sets of collagen fibres at right angles to one another.
In the cuticle of *Rhodnius*, on which the only structure visible on the adult
tergites is a series of transverse ripples, Locke (1959) has demonstrated the
presence both of an antero-posterior gradient and of a side-to-side polarity. The
arrangement of microchaetes on the sternites of *Drosophila* suggests that the
field is isotropic; compare the transverse rows, Text-fig. 1 *d*, with the diagonal
rows, Text-fig. 1 *e*. But on the dorsal surface of the thorax there are reasons for
supposing that the ‘rows’ and ‘columns’ are separately determined. There is a
constant number of antero-posterior rows of microchaetes, the spacing between
rows being appreciably greater than between bristles within a row. A connexion
between the mechanisms responsible for the arrangement of macrochaetes and
of microchaetes is also indicated, since the two pairs of dorsocentral macro-
chaetes always occur in the fifth row of microchaetes, counting from the mid-
dorsal line, and each macrochaete occupies a position in the row which would
otherwise be occupied by a microchaete.

**SUMMARY**

The bristles of *Drosophila* fall into two classes, the microchaetes which are
small, numerous, and which vary in number from individual to individual, and
the macrochaetes, which are larger, fewer in number, and constant in arrange-
ment within a species, although many mutants which alter their number are
known. Variations in the arrangement of macrochaetes in populations of D. subobscura homozygous for the mutant ocelli-less are interpreted in terms of variations in a 'prepattern' determining the positions of the bristles, and of the competence of cells to respond to this prepattern by forming bristles. A process whereby such a prepattern may develop is described. It is argued that the arrangement of the microchaetes is determined by a similar process, differing only in that it is less accurately regulated. Mechanisms which may increase the accuracy of prepattern formation are discussed.

RÉSUMÉ

La disposition des soies chez la Drosophile

Les soies de Drosophila se répartissent en deux catégories. Les microchêtes sont petites, nombreuses, et leur nombre varie d'un individu à l'autre. Les macrochêtes sont plus grandes, moins nombreuses, et leur disposition est constante pour une espèce donnée, bien qu'on connaisse un grand nombre de mutations modifiant leur nombre. Des variations dans la disposition des macrochêtes, chez des populations de D. subobscura homozygotes pour la mutation sans ocelles, sont interprétées en termes de variations d'un 'pré-arrangement' déterminant la position des soies, et de la compétence des cellules à réagir à ce 'pré-arrangement' en formant les soies. On décrit un processus selon lequel ce 'pré-arrangement' pourrait se réaliser. On soutient que la disposition des microchêtes est déterminée par un processus similaire, en différant seulement par une régulation moins précise. On discute des mécanismes qui pourraient accroître la précision de la formation du 'pré-arrangement'.

ACKNOWLEDGEMENTS

This work was supported by a grant from the Nuffield Foundation, whose assistance is gratefully acknowledged. Our thanks are also due to Mrs. Sheila Maynard Smith, who provided the solutions of Turing's equations shown in Text-fig. 1.

REFERENCES


*Manuscript received 18: v: 61*