VARIATION OF SCUTELLAR BRISTLES IN DROSOPHILA.

VIII. SELECTION AND POLYGENES

RAJA F. NASSAR¹

Department of Genetics, University of California, Davis

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MATHER (1941) proposed the "polygene" hypothesis to explain the alternations of periods of slow and sudden responses to selection which occurred in his experiments, and in those of PAYNE (1918). Similar patterns of response to selection have been found by SISMANIDIS (1942); THODAY and BOAM (1961); FRASER and HANSCH (1964); FRASER, SCOWCROFT, NASSAR, BRAVO and ANGELES (1965). This phenomenon of sudden responses to selection is clearly distinct from the predictable, relatively smooth type of advance which is exemplified by the results of CLAYTON, MORRIS and ROBERTSON (1957).

A feature of many of the above experiments which showed sudden responses is that they involved an initial restriction to very few parents. It is possible that the alternation of slow and fast responses found in these experiments is due to the incorporation of a "genetic bottleneck" causing a restriction of the genetic variability, with a resultant selection on individual polygenes.

Restriction of genetic variability to few parents should result in a decrease in the advance which can be achieved by selection, unless the genetic system involves a restriction in the expression of genetic variability which can only be overcome by intense selection pressures. The arrangement of genes in polygenes could produce such a restriction. If the polygenic system involves more than additive and dominant types of gene actions, restricting variability to few parents could then cause rapid responses to selection. If such is the case, it is of importance to know whether restricting genetic variability to only part of the genome would increase the frequency and magnitude of such response.

Restriction of genetic variability to one chromosome can be accomplished in *Drosophila* by using the "balancer" chromosomes. The object of this study is to restrict variability to each of chromosomes 1, 2 and 3, and to observe the effects of selection when practiced on one chromosome as compared to the whole genome. Selection was for increase number of scutellar bristles.

A summary of this work has been published by NASSAR and FRASER (1965). In this paper, however, the author presents all the data with a more extensive analysis of the results.

¹ Present address: Department of Animal Husbandry, Institute of Agriculture, University of Minnesota, St. Paul, Minnesota 55101.

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MATERIALS AND METHODS

Three sets of ten lines of *Drosophila melanogaster* were constructed in which specified chromosomes from a variable laboratory stock (70) were introduced into an isogenic stock (Isogenic 5a-8). The first set of lines involved only the 1st (X) chromosome, and in each line a random sample of two variable 1st chromosomes from Stock 70 was introduced into Isogenic 5a-8 (see pair mating, Table 1). Similar lines were formed for the 2nd and 3rd chromosomes with four variable chromosomes from Stock 70 in each. The crosses used in this chromosomal transfer are described in Tables 1, 2 and 3. The multichromosomal balancer stock used in the transfer was $Y^{s1} Sc^8/Y^{s1} Sc^8; Cy/Pm; D/Sb$. Twenty parents from Stock 70 were used in the first cross of each transfer. The number was maintained as such for every cross thereafter till the last cross which was a single-pair mating. Ten such single-pair matings gave rise to the ten lines (one pair mating for one line) in each of the 1st, 2nd and 3rd chromosome sets. Two sets of control lines were maintained. One set of ten lines were started from Isogenic 5a-8, and another set of 30 lines was started from Stock 70. Each line originated from a single female. Selection was then practiced for increased number of scutellar bristles in females. Selection was maintained at the 5% level in all sets of lines. It was based on 40 females per generation per line in Isogenic 5a-8 and 80 females in the rest of the sets of lines. Two females and 2 males (randomly chosen) were retained as parents of the next generation in Isogenic 5a-8 lines; and 4 females and 4 males (randomly chosen) were retained as parents in all other lines. Selection was practiced in sets 1, 2 and 3 for 13 generations, and in each of the Isogenic 5a-8 and Stock 70 lines for 12 generations. Ten of the 30 lines from Stock 70 were maintained until the 15th generation. The ten initial lines of Isogenic 5a-8 (base stocks) were maintained by mass transfer and their scutellar means measured at the 12th generation for comparisons with the scutellar means of the ten selected lines of Isogenic 5a-8.

For each line of the sets, the regression of mean scutellar bristle number on number of generations was calculated. No attempt was made to assess the exact magnitude of response that was genetic or environmental. The interest was in the comparisons of the 1st, 2nd and 3rd chromosome lines with Stock 70 for the effectiveness of selection.

TABLE 1

Transfer of chromosome 1 from Stock 70 to Isogenic 5a-8, for 1st chromosome lines

TABLE 2

Transfer of chromosome 2 from Stock 70 to Isogenic 5a-8, for 2nd chromosome lines

TABLE 3

Transfer of chromosome 3 from Stock 70 to Isogenic 5a-8, for 3rd chromosome lines

TABLE 4
Regressions of mean scutellar bristle number on number of generations for 5a-8, 1, 2, 3, and 70 sets

5a-8	1	2	3	70
.158 ± .067	-.0002 ± .0105	.017 ± .008	.090 ± .036	.029 ± .009
.054 ± .030	.047 ± .016	-.001 ± .007	.178 ± .056	.058 ± .017
.051 ± .029	-.007 ± .012	.005 ± .007	.270 ± .091	.037 ± .012
.030 ± .029	.023 ± .017	-.0006 ± .004	.055 ± .020	.045 ± .014
.049 ± .022	.024 ± .020	.007 ± .007	.001 ± .008	.026 ± .011
.012 ± .029	.025 ± .011	-.011 ± .014	.002 ± .005	.0003 ± .0004
.038 ± .025	.047 ± .016	.016 ± .008	.136 ± .043	.004 ± .002
.057 ± .028	.018 ± .008	-.003 ± .005	.066 ± .023	.001 ± .001
.051 ± .029	.062 ± .025	.040 ± .015	.016 ± .006	-.0005 ± .0013
.109 ± .041	.086 ± .032	-.020 ± .013	.249 ± .082	.001 ± .0007
				-.001 ± .003
				.009 ± .004
				.012 ± .005
				.007 ± .002
				
				0.014 ± 0.001

TABLE 5

*Means of scutellar number at initial and last generation of selection**

5a-8			1		2		3		70	
Initial generation	Last generation	Base stock	Initial	Last	Initial	Last	Initial	Last	Initial	Last
6.07	7.62	6.68	5.61	5.47	4.43	4.60	5.72	7.11	4.00	4.25
5.79	6.15	6.74	5.58	6.61	4.34	4.35	4.35	6.46	4.16	4.70
6.00	6.32	6.95	6.14	5.41	4.32	4.21	4.53	8.33	4.05	4.63
6.38	6.45	6.63	5.13	5.31	4.32	4.35	4.78	5.57	4.03	4.90
5.46	6.00	6.33	5.44	5.28	4.36	4.33	4.17	4.23	4.00	4.40
5.57	6.02	6.08	4.12	4.46	4.80	4.46	4.11	4.31	4.00	4.02
5.75	6.02	6.20	5.16	5.88	4.23	4.51	4.25	5.75	4.00	4.05
5.80	6.35	6.65	4.24	4.38	4.28	4.26	4.17	4.76	4.03	4.03
5.43	6.12	6.68	4.41	5.48	4.53	4.70	4.15	4.33	4.06	4.03
5.36	6.20	6.38	4.73	5.71	4.79	4.55	4.50	6.91	4.03	4.03
5.72	6.32	6.53	5.07	5.40	4.44	4.43	4.47	5.77	4.04	4.30

* The ten lines of Stock 70 that were selected for 15 generations are included in the table.

FIGURE 1.—Selection response (scutellar number) *vs.* number of generations in each of the sets. From left to right: a. Isogenic 5a-8 control. b. Set 1 (Chromosome 1 substituted: $1_{70} 2_{5a} 3_{5a}$). c. Set 2 (Chromosome 2 substituted: $1_{5a} 2_{70} 3_{5a}$). d. Set 3 (Chromosome 3 substituted: $1_{5a} 2_{5a} 3_{70}$). e. Stock 70 control. The repeat score of unselected lines at Generation 12 is shown by dots indicated by the arrow in a. These dots have been misplaced to the left.

RESULTS

The results are shown in Figure 1 and in Tables 4 and 5. Isogenic 5a-8 had a high mean scutellar number of 5.72. Substitution of chromosomes from Stock 70 markedly reduced this in all but a fraction of the 1st chromosome lines and one of the 3rd chromosome lines. Tables 4 and 5 reveal that there has been a very slight response in the 1st chromosome and Stock 70 lines, no response in the 2nd chromosome lines, and a very dramatic response in the majority of the 3rd chro-

mosome lines. The 5a-8 lines showed an apparent response. Scores of the unselected Isogenic 5a-8 base stocks at the 12th generation showed that the response was due to an environmental trend, since a paired t-test showed no significant difference at 5% level between the scutellar means of the base stocks and the means of Isogenic 5a-8 lines at the last generation of selection.

For the purpose of comparisons concerning the effectiveness of selection we are faced with the familiar question as to what is the best control to use? Both Stock 70 and Isogenic 5a-8 represent two genetic extremes (heterozygosity *vs.* homozygosity), while the 1st, 2nd and 3rd chromosome lines are intermediary in this respect. It is very difficult to know how environmental changes effect each of these sets of lines. If heterozygosity is a cause of environmental stability, then it is expected that environmental effects are most in 5a-8, least in Stock 70 and intermediary in the rest of the lines.

When Isogenic 5a-8 is used as a control with an average regression coefficient of .06, it is revealed that Stock 70 lines, 2nd chromosome lines and almost all of 1st chromosome lines show a negative change in bristle number. At least five 3rd chromosome lines show a positive change in bristle number that is greater in magnitude than that of the control. This difference from the control can be attributed to genetic effects. If, however, Stock 70 is used as a control, it appears that there has been a slight positive response in some of the 1st chromosome lines, a positive response in Isogenic 5a-8, no response or a slightly negative response in some of the 2nd chromosome lines and a large positive response in majority of the 3rd chromosome lines. This leaves no doubt, regardless of which control is used, that a good portion of the 3rd chromosome lines showed greater genetic effects in selection, irrespective of its magnitude, than that shown by Stock 70 lines. This is also clearly shown in Figure 1.

DISCUSSION

The lack of response in the 2nd chromosome lines is in accord with previous selection experiments (FRASER *et al.* 1965) initiated from Stock 70 in which there has been little involvement of the 2nd chromosome. The lack of a greater response in the 1st chromosome set was not expected since this chromosome has been frequently involved in responses found in selection lines from Stock 70.

In this experiment, however, chromosome 1 carried the recessive gene white honey (w^h). Plum (Pm) is not detected in the presence of w^h . This means that on the average about one half of 1st (X) chromosome lines carried a Pm 2nd chromosome which was variable.

The marked advances found in the 3rd chromosome lines differ markedly from the sudden advances found in other experiments by FRASER *et al.* (1965) in that there was no lag and a much higher proportion of the lines showed an advance which in some instances was higher than ever reached before in the same period of selection. Less than 10% of all previous lines selected from Stock 70 by FRASER *et al.* (1965) showed a sudden response after a lag of 5 to 10 generations. The heterogeneity of response in the ten lines of the 3rd chromosome (Tables 4 and 5)

can be due to the effects of random sampling and perhaps drift, since single females were sampled to initiate each line. A more extensive study of the frequency of response to selection in the 3rd chromosome lines would be of interest.

The control selections from Stock 70 established in parallel with present experiments have shown no sudden advances by the seventh generation in 30 lines; a most striking contrast.

A question that arises is whether the comparison of 3rd chromosome lines with Stock 70 lines is adequate in view of the fact that their starting points were different. A look at 2nd and 1st chromosome lines, however (Table 5), shows that their starting points were different from 70 and as high and higher than that of 3rd chromosome, yet there was no striking difference in response from 70. This argues against any response in the 3rd chromosome lines being affected by its starting point although it does not completely exclude such possibility.

There are several possibilities for explaining the results of the selection response on the 3rd chromosome.

(1) Restricting variability to the 3rd chromosome might have resulted in a differential reduction in the forces of artificial and natural selection. If natural selection is of importance as a force counteracting artificial selection, then a proportionately greater reduction in this force as compared to that of artificial selection can enhance response on the 3rd chromosome. However, this is a remote possibility since fitness was not observed to be involved in the selection lines of this experiment.

(2) Restricting variability to the 3rd chromosome might have increased heritability by reducing the nonadditive (mainly epistatic) more than the additive genetic effects. This was essentially the explanation given in an abstract on these results published earlier by NASSAR *et al.* (1965). An hypothesis of this sort can, of course, be tested directly. It can also explain the enhancement of response, but does not allow for a greater response at the limit in the 3rd chromosome as compared to Stock 70. The limit, however, can be approached more rapidly in the case of the 3rd chromosome, and might not be achieved in Stock 70 within the duration of an experiment.

(3) Genetic models can be proposed that might be meaningful in the light of these results. A model would have to take into account the fact that with regard to the scutellar character, fixing a portion of a set of controlling genes at the outset has increased the probability of obtaining good genotype(s) as well as of reaching a higher level of selection response.

Model I: Let us assume that there is at least one negative overdominance locus on chromosome 1 with the rest of the loci on chromosomes 1 and 3 being additive. Consider the matrix of values in terms of concentration of the underlying morphogenetic substance.

	a_1a_1	a_1A_1	A_1A_1
a_3a_3	2	0	2
a_3A_3	3	1	3
A_3A_3	4	2	4

If the best genotype is $A_1A_1A_3A_3$ or $a_1a_1A_3A_3$, then the probability of obtaining this genotype when all genes are segregating is

$$(P^2_{A_1} \times P^2_{A_3}) + (P^2_{a_1} \times P^2_{A_3})$$

The probability of obtaining the best genotype when only A_3-a_3 is segregating and A_1-a_1 is fixed is $P^2_{A_3}$ which is a higher probability.

Model II: Let us assume that there are at least two loci, one on each of chromosomes 1 and 3, that interact in a duplicate dominant epistatic manner. Consider the matrix of values in terms of concentration of the underlying morphogenetic substance.

	B_1B_1	B_1b_1	b_1b_1
B_3B_3	1	1	1
B_3b_3	1	1	1
b_3b_3	1	1	4

The probability of obtaining the $b_1b_1b_3b_3$ genotype when both loci are segregating is $P^2_{b_1} \times P^2_{b_3}$. This probability, however, increases to $P^2_{b_3}$ when B_1 locus is fixed homozygous b_1b_1 and the B_3 locus is segregating. In this model, one gene can be at high frequency while the other is at low frequency. This then would have its effect on which lines (1st or 3rd chromosome) make the most progress.

The expected frequency of response and its limit, given enough time, would for such models be the same for each of the 3rd chromosome and 70 lines. But, within a time limit of a selection experiment, this expected frequency and limit of response might easily not be achieved in Stock 70 especially when one considers that a number of loci (more than two) might be involved in the scutellar expression.

Once a good genotype is obtained its rapid spread in the small population under selection can readily move the population mean from a low to a high level (peak). The rapidity of a shift from a low to a high peak in a small population depends in this case on gene frequency and chance. These models have no stable equilibrium and will lead to fixation of the best genotype.

In view of these models, it is of importance to repeat this experiment in several different isogenics and observe the frequency of response on 1st and 3rd chromosomes.

In *Drosophila melanogaster* it is known that there are genes for bristle number on the 1st and 3rd chromosomes (PAYNE 1918; FRASER *et al.* 1965). A major question in view of the experimental results is whether the limit, when selection is practiced on one chromosome, is greater than can be achieved from selection on the whole genome. This could not occur in a simple genetic system involving additive and dominance effects, but in terms of an increased heritability or the models described above, the likelihood of approaching the limit in a short time would be greater for the 3rd chromosome as compared to the whole genome.

In the 13 generations of this experiment, the genetic potential of the 3rd chromosome alone was able to produce greater responses than the total potential of all chromosomes in Stock 70 from which they were derived. These responses were also greater than previous lines selected for 25 generations (FRASER *et al.* 1965).

However, no record of the selection intensity has been maintained in those lines. It could have been less intense than in this experiment.

In conclusion, there is evidence that when the 3rd chromosome was segregating and the 1st and 2nd chromosomes were isogenic selection caused greater responses than when all three chromosomes were segregating. This kind of result suggests that the scutellar genetic system is complicated beyond additive and dominance effects. The possibility that Isogenic 5a-8 has caused such peculiar results should not be excluded at this stage. It is highly desirable therefore to test for a generality of such results in future experiments.

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SUMMARY

Three sets of lines were constructed in which specified chromosomes from a variable stock (70) were introduced into an isogenic stock (Isogenic 5a-8). The first set involved only the 1st (X) chromosome, and in each line two 1st chromosomes from Stock 70 were introduced into Isogenic 5a-8. Similar lines were formed for the 2nd and 3rd chromosomes with four variable chromosomes in each.

Two sets of control lines were maintained. A set of lines was started from Isogenic 5a-8. The second set of 30 control lines was started from Stock 70. Selection was then practiced in all the lines for increased number of scutellar bristles.

The results showed that the 3rd chromosome line gave higher responses than any of the other lines, and in particular the 70 lines. Epistasis and a negative overdominance model are proposed as possible explanations. The possibility is left open, however, that such results might have been a property of Isogenic 5a-8. More experimental evidence is needed to test the generality of the observed results.

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