FITNESS AND ARTIFICIAL SELECTION

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Received 29.xii.60

1. INTRODUCTION

It is usual to find that viability and fertility decline in lines that are subjected to selection for metric characters not evidently directly concerned with these components of fitness. When the artificial selection is relaxed, natural selection tends to restore viability or fertility, and there is corresponding loss of some of the results of selection (see Lerner, 1954).

Mather and Harrison (1949) have argued that such results are in no simple way to be interpreted in terms of pleiotropic effects, their evidence pointing to linkage of fertility genes to those affecting the primary character under selection. Breese and Mather (1960) have obtained confirmatory evidence, and the results of Clayton, Morris and Robertson (1957) accord with this view in showing that the rate and extent of reversion under relaxed selection are not completely correlated with the extent of response under forward selection.

The extent to which the response to selection for a character, such as bristle number in *Drosophila*, may be affected by fertility genes not directly influencing that character itself, could be conveniently tested if it were possible to assess the effect on a selection line of a gene with no detectable effect on bristle number, but with considerable effect on viability or fertility. The occurrence of a mutation of this kind in a line of *Drosophila melanogaster* under selection for sternopleural chaeta number gave us the opportunity to perform such a test. The results are reported here.

2. MATERIALS AND METHODS

(i) Material

The mutant was found as a single male in the fifteenth generation of a line under selection for low chaeta number. The selection line was homozygous *vg* having been initiated from the vestigial segregants in the F_2 of a cross between a vestigial stock and inbred Oregon wild type. The mutant male had strap-like wings. It was mated to a single vestigial sister and produced 58 strap and 40 vestigial progeny, a ratio not significantly different from 1:1 ($\chi^2 = 3.31$) but having a suggestive excess of "strap". "Strap" flies from this progeny were mated together and their progeny contained 151 wild type, 356 "strap", and 122 vestigial flies, a significant deficiency of vestigial. These results suggested that the mutant arose from a partial back mutation of *vg* to an allele similar to the pennant alleles (Bridges and Brehme, 1944) and that the mutant allele raised the viability of flies relative to *vg*.

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The mutant might of course have been a suppressor at another locus, but this possibility was virtually eliminated. Homozygous "pennant" flies were mated to wild type and F_1 females were mated to vg/vg males. Some 13,000 progeny were obtained and these were wild type and heterozygous pennant/vestigial ("strap") in 1 : 1 ratio. No vestigial progeny occurred. The mutant was therefore designated vg^{pD} (vestigial pennant of Dinsley).

One pair of offspring from the original mutant male and his mate (vestigial sister) was used to start a vg^{pD}/vg stock which was maintained thereafter by transferring five pairs of heterozygotes each generation. Three generations later this stock was used to establish two low selection lines, one homozygous pennant and the other homozygous vestigial.

In addition, two backcross lines were started in order to transfer the pennant gene into a high vestigial line ("vg 6" of Thoday and Boam, 1961) that was thought to be approaching a plateau. It was not near its plateau, but continued responding for a further 40 generations, so the two backcross lines were maintained for this time. This was done by crossing vg/vg^{pD} females to males of "vg 6" in each generation, and repeating with the heterozygous female progeny in each subsequent generation. Selection lines were in due course taken from these backcross lines as will be described below.

(ii) Selection Methods

The selection lines to be described here were maintained exactly as other directional selection lines maintained in Sheffield (see Thoday, 1958). There were four single-pair cultures per generation, with a rotational mating system maintaining the four female sub-lines as one population. Twenty of each sex from each culture of each generation were assayed for chaeta number, and the best fly from each 20 was used to maintain the line. The next three flies were set up in three further single-pair cultures to insure against failure of the first culture, so that 16 single pairs were set up per line per generation. The number of flies emerging in the first four days of emergence in the first successful culture of each sub-line was recorded as a measure of fertility and viability and is referred to below as the productivity of the line. The number of single-pair cultures that proved sterile was also recorded.

3. RESULTS

(i) Vestigial, pennant and fitness

Tests were made to confirm the conclusion, suggested by the initial data, that the pennant gene increased the fitness of flies relative to vestigial.

One test was made by determining the effect of natural selection on heterozygous populations. Six population bottles were set up from the vg^{pD}/vg stock. By the tenth generation the gene vg had been eliminated from all the six populations. No homozygous vg flies occurred after the sixth generation. In these conditions natural selection strongly favoured pennant at the expense of vestigial. Part of this result was shown to arise from the greater success of pennant males in obtaining mates, the inferiority of vestigial males being pronounced. Pennant homozygotes were somewhat superior to heterozygotes in this respect.

The first generation of these populations, being progeny of pennant heterozygotes, provided a test of relative viability. There were 207 homozygous pennant, 337 heterozygotes, and 127 homozygous vestigial flies, a clear deviation from the 1:2:1 ratio to be expected if there were

no viability disturbances ($p < 0.001$). These data are consistent with expectation based on $(p+q)^2$, and thus provide no evidence for heterosis ($p < 0.7 > 0.5$). Six further comparable tests were made and gave a total (excluding those above) of 760 pennant, 1327 heterozygous and 568 vestigial flies, against an expected 663.75, 1327.5, 663.75, and leave no doubt of the effect of pennant on viability during larval and/or pupal development.

Tests were also made to determine whether pennant and vestigial flies differed in fertility. Table 1 shows the number of progeny produced by 18 successful single-pair cultures of each of the four types of cross. The parents came from the vg^{pD}/vg stock. Thirty-six cultures had been set up and the number of sterile matings is recorded. There

TABLE 1
Fertility of vestigial and pennant flies

Cross female $\times$ male	Sterile matings	No. of progeny from 18 fertile cultures
$vg^{pD}/vg^{pD} \times vg^{pD}/vg^{pD}$	0	2172
$vg^{pD}/vg^{pD} \times vg/vg$	11	2250
$vg/vg \times vg^{pD}/vg^{pD}$	3	1556
$vg/vg \times vg/vg$	18	1313

is no doubt that matings involving vestigial males are more often sterile ($p < 0.001$), and there is similar evidence, though less strong, that the same applies to vestigial females ($p < 0.05 > 0.02$). It seems further that, if successfully mated, pennant females produce more progeny than vestigial females.

The origin of pennant, and the method of establishment of the vg^{pD}/vg stock, make it rather unlikely that these effects are due to genes at any locus other than vg . We conclude that vg^{pD} is a gene that has a considerable effect on many aspects of fitness, making its possessors superior to vg/vg flies.

(ii) *Pennant, vestigial and chaeta number*

The mean sternopleural chaeta numbers of the pennant, heterozygous and vestigial flies in 6 vg^{pD}/vg sub-lines of the vg^{pD}/vg stock are listed in table 2. Each entry is based on 20 flies of each sex from each of four cultures. The analysis of the variance of these means shows that there is some evidence that the different sub-lines differ in chaeta number, but there is no evidence that the genes vg^{pD} and vg have any differential effect on chaeta number.

(iii) *Low selection lines*

As described on p. 114, two selection lines were established from the vg^{pD}/vg stock, one homozygous pennant and the other homozygous vestigial. These lines were maintained for 25 generations.

Figure 1 illustrates the results of selection. For the first 12 generations the two lines responded together, and there is no evidence that their chaeta numbers differed. The productivity of the pennant line was, however, much higher than that of the vestigial line. After the 12th generation response of the vestigial line ceased, but response of the pennant line continued. There was a coincident fall in the productivity of the pennant line, which brought its productivity down to the level of that of the vestigial line.

TABLE 2
Mean sternopleural chaeta numbers of segregants from 6 vg^{PD}/vg stocks

Stock	Genotype of offspring		
	vg^{PD}/vg^{PD}	vg^{PD}/vg	vg/vg
1	15.77	15.82	16.07
2	16.24	16.12	16.10
3	16.01	15.86	16.00
4	15.69	15.71	15.95
5	15.94	15.81	15.87
6	15.85	15.92	15.90
Mean 1-6	15.92	15.87	15.98
<i>Analysis of variance</i>			
Source	n	Mean square	P
Genotypes .	2	0.01785	0.2
Stocks .	5	0.04714	<0.05
Interaction (error)	10	0.00944	>0.01
Total .	17	...	...

It might be supposed that the vestigial line was, by generation 11, homozygous at all loci affecting chaeta number, but this was not so. The mean chaeta number of a relaxed selection line taken from it at that generation rose significantly.

Not only were the productivities of the two lines different in the first 10 generations, but their "sterilities" also differed. In the first 10 generations 10 single pair matings failed in the pennant lines (16 set up each generation (see p. 114)). There were 70 comparable failures in the vestigial line. In the second 10 generations 26 failed in the pennant and 64 in the vestigial lines. In 10 generations of relaxed selection there were 13 pennant failures and 40 vestigial failures.

We therefore have a strong suggestion that the greater "fitness"

of pennant does permit more extreme results from selection. At the same time, there is no evidence that it affects the initial rate of response to selection.

(iv) *The first high selection lines*

As *vg* 6 had been expected to reach a plateau soon after the backcrossing programme was begun, high pennant and vestigial selection lines were set up after only 7 generations of backcrossing. Three pairs of sister selection lines, each comprising one *vg/vg* and one *vg^{vd}/vg^{vd}*

FIG. 1.—The mean chaeta numbers and the productivities of the pennant and vestigial low selection lines. Solid lines : pennant. Dotted lines : vestigial.

line were started from three separate cultures of one of the backcross lines.

As might be expected, the chaeta numbers of the *vg/vg* lines were at the start higher than those of the pennant lines. Productivity of the pennant lines was higher than that of the vestigial lines. The lines were selected for high chaeta number for 11 generations, after which other commitments forced us to cease selection. They were maintained thereafter by 6-pair transfers without selection for a further 20 generations. The results are summarised in table 3.

The table shows clearly the greater productivity of the pennant lines. There is evidence of a decline of productivity with selection in the vestigial lines, but negligible evidence of a similar decline in the pennant lines. There is no evidence that this productivity difference

affected the rate of response to selection. There is, however, strong evidence that it did affect the changes under relaxed selection, for the pennant lines lost fewer chaetæ than the vestigial lines.

TABLE 3
Results from the first high lines

Lines	Initial chaeta no.	Initial productivity	Chaeta no. after selection	Productivity after selection	Chaeta no. after relaxing selection	Fall
P_1	27.7	115	31.2	110	30.2	1.0
V_1	29.2	82	31.1	70	23.1	8.0
Difference	-1.5	33	0.1	40	7.1	...
P_2	27.6	100	29.4	80	27.7	1.7
V_2	29.5	76	32.3	44	27.7	4.6
Difference	-1.9	24	-2.9	36	0.0	...
P_3	27.2	130	28.4	125	27.1	1.3
V_3	28.8	70	30.5	35	29.0	1.5
Difference	-1.6	60	-2.1	90	-1.9	...
Means						
P	27.5	118	29.7	105	28.4	1.3
V	29.1	76	31.3	50	26.6	4.7
Difference	-1.6	42	-1.6	55	1.7	...

(v) *The second high selection lines*

After 22 generations of backcrossing to "vg 6", pennant and vestigial segregants of the backcross lines were assayed for chaeta number. At this time "vg 6" was still responding rapidly. Nevertheless the tests demonstrate (table 4) that the pennant flies from the

TABLE 4
Assays of the backcross lines after 22 generations backcrossing to vg 6

	Backcross line	Class of fly		
		Pennant	Heterozygous	Vestigial
Chaetæ/fly	1	40.7	40.2	42.6
	2	40.8	40.2	41.8
Total flies	1	147	296	48
	2	86	186	45

backcross lines were closely approaching the very high chaeta numbers of the vestigial segregants. They also provide evidence that the viability of pennant flies was still greater than that of vestigial flies.

After 40 generations of backcrossing, the line "vg 6" had reached a peak of 46 chaetæ, and fallen back somewhat. At this stage a new homozygous pennant high selection line was extracted from one of the backcross lines and run parallel with "vg 6" itself. The results are given in table 5.

TABLE 5

Mean sternopleural chaeta number and productivity in the vg^{PD}/vg^{PD} high line and in the vg 6 (vg/vg) high line during the same period

Generations	vg^{PD}/vg^{PD}		vg6 (vg/vg)	
	Chaetæ/fly	Productivity	Chaetæ/fly	Productivity
S 0	42.0	33	43.3	28
1	43.8	47	43.4	26
2	45.2	50	43.9	19
3	45.8	50	41.9	24
4	44.8	13	44.5	25
5	44.6	23	43.2	20
6	46.3	44	45.2	25
7	45.1	20	44.8	23
8	45.6	21	44.9	20
Mean 1-8	45.150	33.50	43.975	22.75

It is clear that the pennant line preserved a greater productivity and a higher chaeta number than "vg 6". "vg 6" was also more sterile, and after the two lines had been run together for 11 generations further selection became impossible as "vg 6" had become too sterile to maintain except in mass culture. Once again we have evidence that the gene vg^{PD} increases the productivity of a selection line, relative to vestigial, and that, as in the low lines, this permits the maintenance or achievement of more extreme chaeta numbers. Admittedly these two lines are less strictly comparable than the low selection pair, as the high vestigial line with which the pennant line is compared was not itself segregated from the vg^{PD}/vg backcross line flies. Other commitments at the time prevented us maintaining the further selection line this would have involved. It seems unlikely, however, that this can seriously affect the validity of the comparison.

4. DISCUSSION

The results described above demonstrate clearly that the mutant vg^{PD} , which arose in a vg/vg low selection line had a considerable effect on the fitness of flies possessing it. All the tests, and all the selection lines in which vg^{PD} was later used, agree in showing that vg^{PD} increased the productivity of flies relative to that of flies of closely similar genetic background but homozygous for the gene vg , and the differences in frequency of sterile cultures are striking. There is also

good evidence, both from the specific tests and from the pair of low lines in their earlier history, that the genes *vg* and *vg^{pd}* have negligible differential effect on sternopleural chaeta number.

Both pairs of selection lines, the low lines and the second high lines, provide evidence that the gene *vg^{pd}* permits selection to push chaeta numbers to more extreme values than does the gene *vg*. It seems fair to conclude that it is the greater fertility produced by *vg^{pd}* that makes this possible. This is to conclude that the contribution of *vg^{pd}* to fitness has an additive component which to some extent compensates for the effects of other genes, or gene complexes, selected as a result of selection for extreme chaeta number. Hence the pressure of natural selection against these other genes is reduced in the presence of *vg^{pd}*, and artificial selection can therefore exploit the chaeta number genes more fully.

The behaviour of the first high lines under relaxed selection is in agreement with this conclusion. In the presence of *vg^{pd}*, natural selection pressure was less effective in reducing chaeta number in these lines when the opposing artificial selection pressure was removed.

These results, therefore, support the views and the evidence of those workers who have supposed that correlated responses in "fertility" are responsible for the barriers that are so often met in selection experiments even when the existence of genetic variance of the character under selection can be demonstrated. They further support the conclusions of Mather and Harrison (1949) concerning the possibility that linked fertility genes without pleiotropic effects on chaeta number may often be involved. They seem to demonstrate that the depressed fertility consequent on selection for chaeta number, high or low, whether itself due to pleiotropy or linkage, can be in part compensated for by other loci that have no detectable direct influence on chaeta number. Chaeta number and fertility in a selection line at a plateau are therefore at least partly separable, as Mather and Harrison's experiment also demonstrated.

5. SUMMARY

1. In a homozygous *vg/vg* line that was under selection for low chaeta number, a mutant fly occurred with strap-like wings. The mutant fly was shown to be heterozygous for *vg* and a gene similar to the "pennant" alleles of *vg*.

2. The mutant gene greatly increased the fitness (viability, fertility and mating success) of its possessors relative to *vg/vg* flies, but it had no detectable effect on chaeta number.

3. Sister low chaeta number selection lines were set up from the progeny of the mutant fly and its mate. For 11 generations they had similar though decreasing chaeta numbers, but the pennant line had much greater productivity (number of flies produced per culture). Thereafter response to selection by the *vg/vg* line ceased, but the

pennant line continued to respond. At the same time the productivity of the pennant line fell to that of the *vg/vg* line.

4. The pennant gene was also backcrossed for 40 generations to a high chaeta number *vg/vg* selection line. A homozygous pennant high line was then set up and run parallel with the high *vg/vg* line under selection for high chaeta number. The pennant line had higher productivity and maintained higher chaeta numbers.

5. These and other lines showed that the introduction of a gene (pennant) that increased "fitness", but did not of itself affect chaeta number, to a line reaching the limits of selection for chaeta number, could permit that line to maintain more extreme chaeta numbers. The "fitness" gene also reduced the rate of regression under relaxed selection. It did not, however, affect the rate of forward response until the selection lines approached their plateaux.

6. It is concluded that chaeta number and the fitness of a line at its selection plateau are at least in part affected by different genes.

Acknowledgments.—We would like to acknowledge the help of Mr T. B. Boam, and a grant for technical assistance from the Agricultural Research Council.

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