

"SEX RATIO," MEIOTIC DRIVE, AND GROUP SELECTION IN *DROSOPHILA PSEUDOOBSCURA*

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The processes of meiotic drive and group (interdeme) selection have both been considered capable of having marked effects on evolution. Their importance has been discussed at length (Sandler and Novitski 1957; Wynne-Edwards 1962; Darlington 1959, 1971, 1972), but their action in natural populations has been remarkably difficult to demonstrate.

"Sex ratio" (SR) in *Drosophila pseudoobscura* and other *Drosophila* species has been considered both as a case of meiotic drive (Sturtevant and Dobzhansky 1936; Wallace 1948; Novitski, Peacock, and Engel 1965; Hamilton 1967; Policansky and Ellison 1970) and as one of group selection (Wallace 1969).¹ From data presented here, I argue that it is misleading to consider the case of SR in nature as one of meiotic drive, since it is a special case; moreover, there is no evidence for the action of group selection.

Meiotic drive.—The term "meiotic drive" was introduced by Sandler and Novitski (1957) to describe cases in which "heterozygotes of certain constitutions fail to produce the two kinds of gametes with equal frequency." Such behavior, they pointed out, could drastically alter allelic frequencies in populations. They originally applied the term to those cases where the "force" was a consequence of the mechanics of the meiotic divisions.

Cases of segregation ratios different from 1:1 have been reported in several plants and animals (for review see Zimmering, Sandler, and Nicoletti 1970). Perhaps the best-understood naturally occurring case in plants is that of the knobbed chromosomes in corn (Rhoades 1952). In animals the *t*-alleles in mice (Dunn 1953; Lewontin and Dunn 1960; Lewontin 1962, 1968), the "segregation distorter" (SD) locus in *Drosophila melanogaster* (Sandler, Hiraizumi, and Sandler 1959), and the "sex ratio" factors in various *Drosophila* species (Gershenson 1928; Sturtevant and Dobzhansky 1936; Stalker 1961) are the best-studied naturally occurring cases.

All have been difficult to understand. The position of the SD locus is known quite precisely, and it is known that the development of the SD+ spermatids is interfered with (Tokuyasu, Peacock, and Hardy 1972); but

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¹ The chromosomal, sex-linked SR factor, considered here, should not be confounded with the widespread, maternally inherited forms of "SR" which are usually associated with endoparasites (see Poulson 1963 for review).

the phenomenon of SD has given a great deal of trouble to many hard-working investigators, and exactly how it achieves its effect is not understood.

The mode of action of the *t*-alleles is unknown. The nature of the equilibrium of the frequencies is not agreed upon (Lewontin 1962, 1968; Johnston and Brown 1969; Levin, Petras, and Rasmussen 1969). The problem is complicated by the volatile nature of the *T* locus and the great number of naturally occurring alleles found at it.

Although first described by Morgan, Bridges, and Sturtevant (1925), the mode of action of SR was not understood until very recently (Policansky and Ellison 1970). Because of the misunderstanding of the action of SR, the population dynamics has also not been understood. The genetic nature of the SR factor is still unknown.

In spite of the rarity and intractability of naturally occurring cases of meiotic drive in animals, it appears likely that meiotic drive is of evolutionary significance. One of the greatest difficulties in studying naturally occurring meiotic drive is that the segregation distortion must be large to be noticed, yet it has to be balanced by counteracting selection if the driven allele is not to become fixed and thus undetectable.

Group selection.—Group selection has been defined in slightly different ways by different authors, but the essential idea is that it leads to adaptations that are advantageous to groups rather than individuals. Group-related adaptations should be distinguished from attributes of groups which are the aggregate effects of individual adaptations. The idea of group selection is an old one. Fisher (1958) argued against it; he said: "The principle of Natural Selection . . . affords a rational explanation of structures, reactions and instincts which can be recognised as profitable to their individual possessors. It affords no corresponding explanations for any properties of animals or plants which, without being individually advantageous, are supposed to be of service to the species to which they belong." Darwin (1859) spoke of natural selection as acting "only by the preservation and accumulation of small inherited modifications, each profitable to the preserved being."

Wynne-Edwards (1962) is an ardent proponent of group selection as the explanation for adaptations which cannot be explained on the basis of genic selection. Darlington (1959, 1971, 1972) attributed to group selection the power of speeding evolution and of opposing genic selection. Lewontin (1962) used group selection to explain the fact that the frequency of *t*-alleles in wild mouse populations was lower than expected on the basis of their segregational advantage; Wallace (1969) postulated a similar balance between meiotic drive and group selection for SR in *Drosophila pseudoobscura*. Williams (1966) argued that group selection, while not impossible, is unimportant. He suggested that the principle of parsimony should always lead to the adoption of an explanation of adaptations on the basis of genic rather than group selection.

The opposition to the acceptance of group selection as an important evo-

lutionary force basically hinges on two points. First, conditions necessary for it to be effective are so restrictive that the chance of their all occurring at once is very small (Simpson 1953; Williams 1966; Levin et al. 1969). Second, the reality of group-related adaptations is dubious, and, if they can really be considered as adaptations, they may be explained by genic selection on individuals. To date no adaptation has been demonstrated to be primarily a group-related adaptation which cannot be explained as being of selective advantage to individuals of the group. The negative case of the *t*-alleles in mice (Lewontin 1962) is a possible exception, and the evolution of sex, although incompletely understood, is considered by some (e.g., Fisher 1958) to be a potential product of group selection.

It would be out of place to recount the details of the controversy here. Williams (1966) considered the matter thoroughly and in great detail. His criticisms apply to recent publications of Darlington (1971, 1972). The best approach, I feel, is to consider individual cases on their merits. No general statement is likely to settle the argument at this time.

"*Sex ratio*."—"Sex ratio" (SR) is a widespread condition of the X-chromosome in *Drosophila*. It causes males to produce progeny consisting almost entirely of females and was first discovered by Sturtevant (Morgan et al. 1925), but the stock was lost before an analysis of the factor could be completed. Gershenson (1928) discovered a similar factor in *Drosophila obscura* and was able to describe it in some detail. He found that it was a sex-linked trait and considered its action to be analogous to that of a gametic lethal, since almost no Y-bearing sperm functioned in fertilization.

Sturtevant and Dobzhansky (1936) found SR in the southwestern states (California, Arizona, New Mexico, Utah, and Colorado) and Mexico in *Drosophila pseudoobscura* and in the Sierra Nevada of California and the coastal mountains of both California and Oregon in the sibling species, *Drosophila persimilis*. SR was always associated with inverted sections in the right limb of the X-chromosome, and Sturtevant and Dobzhansky reported that at meiosis the Y-chromosome degenerates, and the X-chromosome undergoes an extra division, with the result that all four spermatids receive X-chromosomes.

In fact SR in *D. pseudoobscura* is associated with three inversions in the right limb of the X-chromosome (Dobzhansky and Sturtevant 1938; Dobzhansky 1939). The SR sequence in *D. persimilis*, interestingly, is identical with the standard (ST) sequence in *D. pseudoobscura*. The SR sequence in *D. persimilis* differs from the *persimilis* ST sequence by one subterminal inversion in the right limb of the X-chromosome (Dobzhansky 1944).

A puzzling aspect of SR is how its frequency in natural populations is maintained roughly in equilibrium. Sturtevant and Dobzhansky (1936) and Wallace (1948) thought that SR males produced twice as many female progeny as ST (normal) males. Gershenson (1928) was not entirely clear on this matter but seems to have held the same opinion. If this were the case, the SR factor would have a tendency to increase in frequency in natural populations. Sturtevant and Dobzhansky (1936) were unable to

find any evidence for such an increase; they were unable to explain this. They wrote (p. 489): "Wild populations are somehow kept in equilibrium; but the nature of the counteracting force can only be surmised. It must be of such a magnitude that it brings about a result equivalent to the production of only about half as many offspring by a 'sex ratio' male as by a normal one, on the average. Such an influence should be easy to detect experimentally, but preliminary attempts to locate it have not been successful."

Wallace (1948) conducted extensive laboratory investigations into fitness-related characters associated with SR. He analyzed egg production, hatchability of eggs, mortality, and competitive ability in population cages at 16.5° and 25° C. He concluded that "SR possesses a great inherent selective advantage over ST (the standard arrangement) but is prevented from replacing ST in populations because of the extremely low adaptive value of SR/SR females." He also attempted to locate the SR locus on the X-chromosome. The three inversions associated with SR almost never occur separately (Dobzhansky 1944). In two cases X-chromosomes were found with the terminal inversion only, and the one that was tested did not have the SR effect. Wallace obtained a chromosome with the two basal inversions only; he indicated that it retained the SR effect. Beyond this information the actual genic nature of SR remains a mystery.

Barker (1958), Bennett (1958), and Shaw (1959) calculated equilibrium frequencies for SR using Wallace's (1948) estimates of fitness. These estimates do not correspond to Wallace's results from population cages. Barker suggested other fitness values ($SR/SR = 0.0$, $SR/ST = 0.4$, $ST/ST = 1.0$, $SR/Y = 0.95$, $ST/Y = 1.0$) for which his calculations produced equilibrium frequencies much closer to those observed by Wallace, but he questioned the validity of estimating various components of fitness and summing them. Infinitely many combinations of fitnesses would give the observed equilibrium frequencies.

Novitski et al. (1965) examined the nature of SR cytologically. They were unable to confirm the earlier report of an extra meiotic division of the X-chromosome, but they photographed the "degeneration" (premature condensation) of the Y-chromosome. They reported that although there was no extra division of the X-chromosome, there were as many sperm per bundle in SR males as in ST males. They explained the phenomenon of SR on the basis of the regular nonfunctioning of meiotic products in the male as proposed for *Drosophila melanogaster* (Novitski and Sandler 1957; Peacock and Erickson 1965).

Cytological studies (Policansky and Ellison 1970) show that SR males produce only about half as many sperm per bundle as ST males, although the full complement of spermatids appears to be present.

Until now the population dynamics of SR has presented an unsolved puzzle. Although data to be presented here do not provide a complete solution to the puzzle, they do shed some light on it.

MATERIALS AND METHODS

Field Studies

Traps baited with rotting bananas were used to trap *Drosophila pseudoobscura* in relatively undisturbed areas near Tucson, Arizona. Immediately upon return to the laboratory flies were immobilized with carbon dioxide, and the *obscura*-group females were isolated and placed in individual vials of cornmeal, agar, and molasses medium. *Drosophila azteca* females are almost indistinguishable from *D. pseudoobscura* females, but males, which appeared in their progeny, are easily distinguishable. Less than 10% of the *obscura*-group flies were *D. azteca*. The *D. pseudoobscura* males were each placed in a vial with two females which carried the recessive markers *sh* (short wing veins, X-chromosome) and *or* (orange eyes, third chromosome). Genotypes of males were determined by scoring their progeny as being either unisexual (SR) or normal. As noted by Gershenson (1928) and Sturtevant and Dobzhansky (1936) and as shown in figure 1, there is rarely any ambiguity as to whether the males are SR. Thus it is not necessary actually to count progeny.

Genotypes of females were determined by mating each of seven of their male offspring with two virgin *sh-or D. pseudoobscura* females (more than 90% of the females caught in nature produced progeny when isolated in vials) and scoring the males' progenies as either SR or ST (see Appendix). The null hypothesis that the populations are in Hardy-Weinberg equilibrium for SR is borne out very well (table 1). The difficulty that the same data are used to determine both gene and genotype frequencies (see Prout 1965, 1969) exists, but its importance is minimized for two reasons. First, gene frequencies were independently estimated in males and females, and found to be extremely close (table 1). Second, the component of the gene frequency of SR contributed by homozygotes is small, only 9% when the frequency of SR is 20%. The error in recognizing heterozygotes is less than 1%; all flies producing both kinds of sons are definitely heterozygous.

The localities of the collection sites were Soldier Trail, at 880 m elevation in the desert foothills of the Santa Catalina mountains north of Tucson (March 1970); Molino Basin, at 1,340 m in oak woodland in the Santa Catalinas (March 1971); and Mount Bigelow, at 2,530 m in fir-Douglas-fir forest, also in the Santa Catalinas (July 1970). The habitats are well described, with photographs, by Patton, Heed, and Lowe (1966). At Molino Basin only gene frequencies were determined.

Laboratory Studies

Policansky and Ellison (1970) showed that SR males produce only about half as many sperm per bundle as do ST males. Four types of experiments were done in the laboratory to attempt to assess the populational consequences of that fact, and to compare them with data obtained from field samples.

I. *Brooding experiment*.—Ten SR and 10 ST males were each placed in a vial containing five virgin *sh-or* females. Males were left in the vials with females for 2 days, then transferred each day for 8 days into new vials each containing five virgin *sh-or* females. Females were isolated in fresh vials immediately following the removal of the males, and they were transferred at intervals of approximately 7 days until they had stopped laying fertile eggs. All females were 4–9 days old before being placed with the males.

II. *Multiple-insemination experiment*.—Dobzhansky and Pavlovsky (1967) reported that multiple insemination occurs in the laboratory in *D. pseudoobscura*; it may also occur in nature (Dobzhansky, Spassky, and Tidwell 1963). The following experiment was undertaken to determine the possible effects of multiple inseminations.

Twenty SR and 20 ST males were each placed in a vial with one *sh-or* virgin female, and left for 4 days. After that time the females were all transferred to new vials. Ten females that had been with ST males and 10 females that had been with SR males were left alone. The other two groups of 10 females had one B-S (wild type from Borrego Springs, Calif.) male introduced into each of their vials. At the same time 10 B-S males were each mated to one virgin female of the same age as those used in the rest of the experiment. Females were about 4 days old at the start of the experiment. After a further 4 days all females were transferred to new vials, and the males were discarded. Females were each transferred twice more at weekly intervals and the total hatching progeny from each female were counted.

III. *Competition experiments*.—To determine the relative ability of the two types of male to compete for and fertilize females, five population cages were set up with different proportions of SR and ST males and ST/ST females. Flies were left in the cages for 3, 10, 13, or 20 days (table 3), and then about 160 females were removed from each cage, each placed in a vial, and allowed to produce progeny.

IV. *Selection experiments*.—Two attempts were made to select lines of SR males that produced higher and lower proportions of males than the parent stock. The first attempt was quickly terminated by mold; the second was continued for six generations (about 10 months) but was completely unsuccessful.

RESULTS AND DISCUSSION

The most striking aspect of the field data (table 1) is that the percentage of females producing unisexual progenies (i.e., females inseminated by SR males) is only about half the percentage of males which have the SR chromosomes. This observation does not appear to be an artifact caused by multiple insemination. Actual counting of progenies of females inseminated in nature yielded a distribution of sex ratios much like that in figure 1; if multiple insemination with sperm mixing were common, a high frequency

TABLE 1
GENOTYPIC AND GENIC FREQUENCIES OF SR FROM NATURAL POPULATIONS
SAMPLED NEAR TUCSON, 1970-1971

	Soldier Trail	Mount Bigelow	Molino Basin
SR/Y	41	41	20
ST/Y	120	204	105
SR/SR	12	9	...
SR/ST	65	96	...
ST/ST	97	236	...
% SR in males*	25.5	16.7	19.4
% SR in females*	25.6	16.7	19.7
Average	25.6	16.7	19.6
No. of females inseminated by SR males ..	36	30	12
%	13.8	7.8	7.6

* "% SR" means the percentage of X-chromosomes tested which bore SR.

of progenies with sex ratios of about 30% males would be expected. If there were replacements of the first male's sperm by that of the second, multiple insemination would not affect the observations. Preliminary results indicate that those females which had been inseminated by SR males produced somewhat fewer offspring than those inseminated by ST males (12 SR progenies averaged 86.1 flies; 150 ST progenies averaged 115.7 flies).

Results of the brooding experiment (fig. 2, table 2) suggest that SR males are only half as fertile as ST. The SR males produced an average of 1,593 offspring each during the 9-day period, while ST males averaged 2,760 each.

Field data, results of the brooding experiment, and the cytological evidence of Policansky and Ellison (1970) suggesting that SR males produce fewer sperm than ST males are all consistent. They suggest that in nature

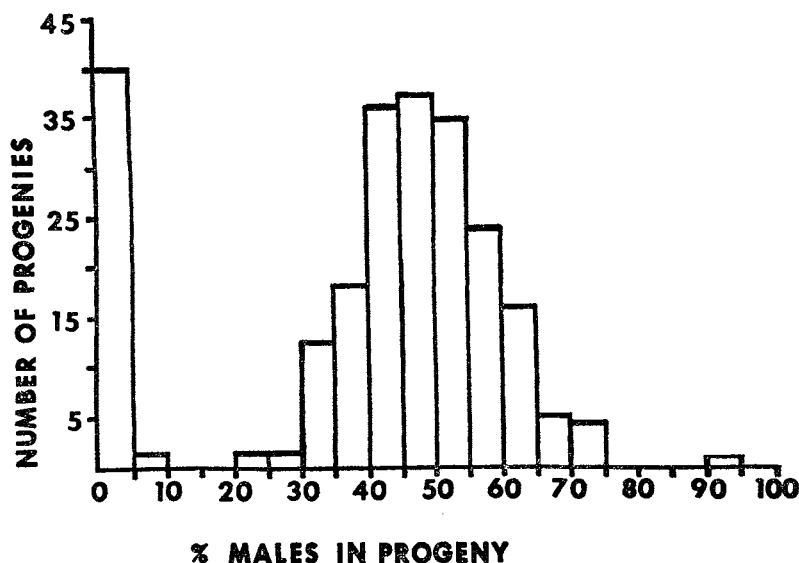


FIG. 1.—Distribution of sex ratios of progenies of males from Soldier Trail, 1970.

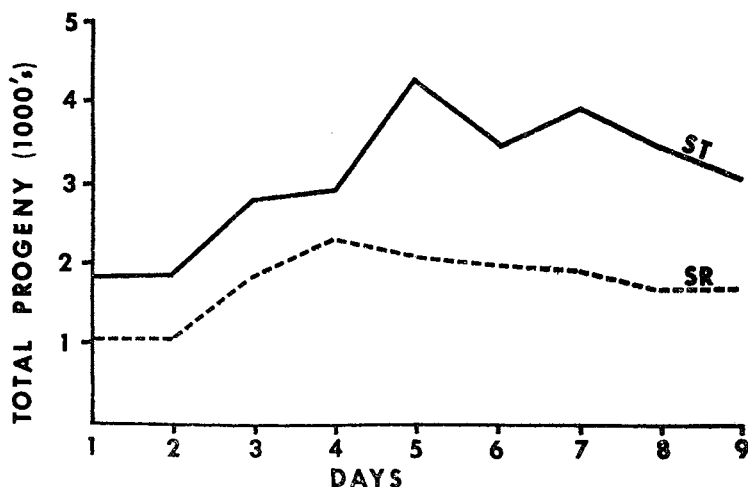


FIG. 2.—Total hatching (adult) progeny produced in 9-day period by 10 SR and 10 ST males.

SR males fertilize only about half as many eggs as ST males. Since each SR male contributes as many X-chromosomes on the average as each ST male, X-chromosomes bearing SR are not at a disadvantage with respect to normal X-chromosomes. It is thus not surprising that the populations appear to be in Hardy-Weinberg equilibrium for SR. There is no evidence from the field of any reduced viability of SR/SR females; they are as frequent as expected on the basis of the gene frequency of SR. This fecundity function has been termed "proportionality" by Hartl (1972).

Although these data strongly suggest that SR males fertilize only half as many eggs as ST males do, it is not clear whether SR males inseminate as many females as ST males do and transfer half as many sperm, or inseminate only half as many females. The exact nature of the deficiency probably does not affect the conclusions drawn, but it is of interest; I thus speculate below as to how it comes about.

TABLE 2
TOTAL NUMBERS OF PROGENY PRODUCED BY 10 SR AND 10 ST MALES IN A 9-DAY PERIOD

DAY	SR			ST			% MALES	
	M	F	Total	M	F	Total	SR	ST
1 and 2	66	2,096	2,162	1,740	1,908	3,648	3.1	47.7
3	54	1,811	1,865	1,360	1,443	2,803	2.9	48.5
4	45	2,281	2,326	1,372	1,521	2,893	1.9	47.3
5	13	2,103	2,116	2,004	2,282	4,286	0.6	46.8
6	17	1,996	2,013	1,675	1,853	3,528	0.8	47.5
7	11	1,904	1,915	1,861	2,041	3,902	0.6	47.7
8	10	1,651	1,661	1,679	1,800	3,479	0.6	48.3
9	16	1,858	1,874	1,477	1,587	3,064	0.8	48.2
Total	232	15,700	15,932	13,168	14,435	27,603	1.5	47.8

NOTE.—The three categories under SR represent the male, female, and total progeny produced by SR males; the next three are those numbers for ST males. The last two columns are the percentages of males in the progenies of SR and ST males.

TABLE 3
ABILITY OF SR MALES TO FERTILIZE FEMALES IN COMPETITION WITH ST MALES

EXPERIMENT	INITIAL POPULATION				TIME		ST	% SR	% FERTILIZED
	SRM	STM	F	% SRM	(DAYS)	SR			
A	12	100	268	10.7	3	9	114	7.3	76.3
B	25	100	300	20.0	3	27	110	19.7	85.6
C	50	200	400	20.0	10	34	127	21.1	94.1
D	25	200	300	11.1	13	10	133	7.0	95.7
E	41	41	300	50.0	20	7	127	5.2	89.3

NOTE.—SRM, STM, F, and % SRM are the numbers of SR males, ST males, and females and the percentage of males which were SR initially introduced into the population cages. Time is the duration of the experiment. SR is the number of unisexual (SR) progenies; ST, the number of normal (ST) progenies; % SR is the percentage of progenies which were SR; % fertilized is the percentage of females which produced progeny of any type.

Results of the competition experiments (table 3) indicate, in those experiments which lasted 13 days or less, that SR males fertilize their share of females. Results are puzzling when the experiment was continued for 20 days; the next generation of flies may have already begun to emerge. By themselves these results are inconclusive, but when they are coupled with results of the multiple-insemination experiment (table 4), an interpretation is possible.

Apparently a female can store enough sperm to fertilize about 200 eggs. If an inseminated female is inseminated again, some sperm are lost if she still has too many from the previous insemination. The 10 females inseminated by SR males produced a total of 1,150 progeny; those inseminated by ST males produced 2,224. When females originally inseminated by SR males were inseminated again, they produced a total of 1,925 progeny. If they had been inseminated originally by *sh-or* ST males, they still only produced 2,142 progeny after the second insemination (table 4, fig. 3).

TABLE 4
PROGENIES PRODUCED BY FEMALES MATED EITHER TO ONE MALE OR TO TWO MALES OF DIFFERENT GENOTYPES

TYPE OF MALE	1ST MATING			2d MATING			1ST AND 2D MATING		
	M	F	T	M	F	T	M	F	T
1st mating, SR	7	1,143	1,150	...	...	...	7	1,143	1,150
1st mating, SR; 2d mating, ST (B-S)	3	707	710	523	692	1,215	526	1,399	1,925
1st mating, ST (<i>sh-or</i>)	1,073	1,151	2,224	...	...	...	1,073	1,151	2,224
1st mating, ST (<i>sh-or</i>); 2d mating, ST (B-S)	725	688	1,413	333	398	729	1,058	1,084	2,142
1st mating, ST (B-S)	788	1,001	1,789	...	...	...	788	1,001	1,789

NOTE.—M, F, T = males, females, total. The numbers represent the number of progeny produced by each mating.

On the basis of the above data, I speculate that in nature SR males inseminate as many females as ST males, but transfer only about half as many sperm per insemination. A female inseminated by an SR male, then, uses up her smaller supply of sperm much more quickly than one inseminated by an ST male and thus becomes receptive to another mating much sooner. So, although SR males inseminate as many females as ST males, only about half the expected number of females in nature produce unisexual progenies, because females inseminated by SR males have their sperm only about half as long as those inseminated by ST males.

The possibility that SR has some adverse effect on the mating success of males, as the mutant yellow is known to do (Tan 1946), is not consistent with the results of either the brooding experiment (table 2, fig. 3) or the competition experiments (table 3). If population densities in nature are really on the order of five adult flies per 100 m² (Dobzhansky and Wright 1943), a slight difference in preference for different types of males would be unlikely to have much of an effect.

Some reservations should be expressed about this explanation. One is the absence of good data on rate of sperm use and on survivorship of adult females in nature. As mentioned above, a small sample indicated that females inseminated in nature by SR males produced somewhat fewer offspring than those inseminated by ST males. In the absence of life-history data it is not possible to decide whether this observation is consistent with the explanation advanced. Another difficulty might involve the rate of sperm use. For the proposed model to work, either a female must "know" how many sperm she has remaining, or she may always be receptive to a second mating but the sperm of the second male do not enter her storage

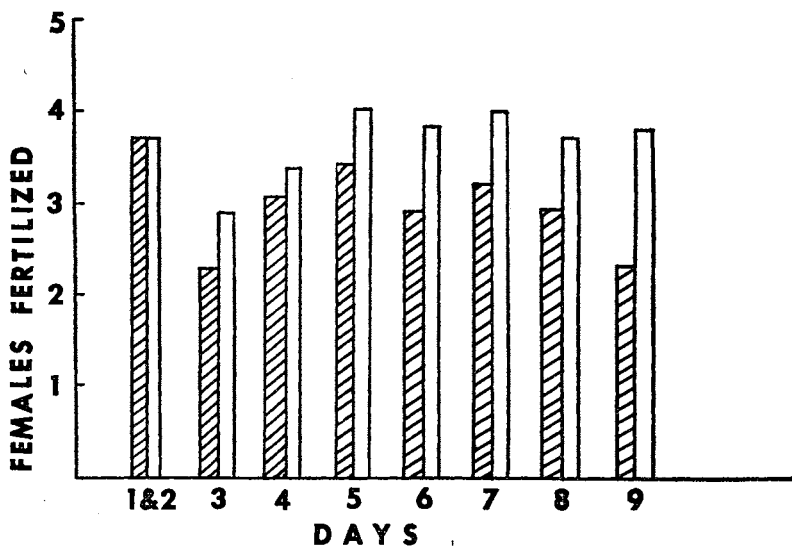


FIG. 3.—Average number of females inseminated per day by SR males (hatched bars) as compared to ST males (open bars).

organs as long as she retains a minimum quantity of sperm or ejaculatory fluid. This area also needs further investigation.

The explanation given requires that adult females in nature live on the average at least 10 days, probably over 2 weeks. As mentioned above, there are no good data on longevity of *Drosophila pseudoobscura* in nature. Females kept in the laboratory commonly survive for 3 months and sometimes produce fertile eggs for as long as 4 months (Tantawy and Vetukhiv 1960). Dobzhansky and Wright (1943) estimated that a population of *or/or* (orange eyes) *D. pseudoobscura* they released on Mount San Jacinto declined by about 9% per day; this means that half the flies lived more than 7.7 days, with a mean longevity of about 10 days. I hesitate somewhat in accepting the validity of these estimates, however. The flies used had been reared in the laboratory, and there is no assurance that their survival is a good measure of the survivorship of wild flies. Second, when this experiment was repeated at Mather (Dobzhansky and Wright 1947), the estimated number of orange flies capturable in a 20-m grid came out much greater than the actual number of flies released, except for the competition factor K' for all days from the third to the sixth, whereas only one such case occurred at Mount San Jacinto. However, it does not seem unlikely that females do in fact live as long as 10 days in nature, on the average. The point should be investigated.

My data clearly show that SR males suffer a loss in their capacity to fertilize eggs proportional to their reduced production of sperm. This has important implications. It is often assumed that the fertility of females is limited by their egg production, which is basically an energy limitation of one sort or another, whereas fertility of males is limited by the number of matings or the availability of females (Bateman 1948; Lack 1954; Bodmer and Edwards 1960; Williams 1966; Cody 1966; Hamilton 1967; Johnson and Cook 1968; Giesel 1972).

In the case of SR males, fertility is at least in part limited by the fact that they have fewer sperm than ST males. I emphasize that this situation almost certainly involves competition; the percentage of wild-caught females producing progeny is about as high as the percentage of females producing progeny in the competition experiments described above. Table 3 shows that even the least crowded cage had a population hundreds of times denser than one would find in nature. The important point, though, is that there is a definite selective advantage to a genotype which produces a greater than average number of sperm. This means that a male cannot devote all the energy he has available for reproduction to seeking out females. The huge size of *Drosophila* spermatozoa (Yanders and Perras 1960; Beatty and Sidhu 1969; Policansky 1970) suggests that the energy devoted to their production is not trivial. This suggestion is strengthened by the observations that none of 10 male *D. pseudoobscura* in the laboratory was unable to fertilize 5,000 eggs in his lifetime (nearly 3 months [Policansky, unpublished data]), and that in *Drosophila melanogaster* all the sperm transferred by a male at one mating may be used in fertilization (Zimmer-

ing and Fowler 1968). Data from the multiple-insemination experiment suggest that an ST *D. pseudoobscura* male is barely able to saturate a female's capacity for sperm at one mating; an SR male is not able to do this at all.

The nature of the selection acting on SR has been puzzling because the chromosome has been assumed to be driven meiotically. Since SR males, on the average, produce as many X-bearing sperm as ST males do, but no more, the SR X-chromosome is not driven (i.e., has no advantage by virtue of aberrant segregation ratios) with respect to the normal X-chromosome. It is driven with respect to the Y-chromosome, but as long as its frequency remains moderately low, the effect is not obvious. Thus I suggested above that SR should be considered a special case of meiotic drive. The Y-chromosome gets a new chance, so to speak, each generation because half the genetic material of each generation comes from males, which bear Y-chromosomes; since the frequency of SR does not change with respect to ST, the proportion of males which are able to produce Y-bearing sperm does not change either.

If they are not driven, why are SR and genes with similar effects so widespread throughout the genus *Drosophila*? These genes are unlikely to have arisen independently many times and to be completely neutral in selective effect and thus found at equilibrium in many populations. The wide geographic and taxonomic distribution of SR suggests that it has been present in some populations, at least, for a long time. The presence of modifier genes in some species (Novitski 1947; Stalker 1961; Hartl 1970) leads to the same conclusion.

A number of possible explanations for the persistence and high frequency of SR exist, although available data do not permit a satisfactory decision.

One possibility is that SR is a device to increase the proportion of females in natural populations. If one male can fertilize more than one female, then a population with a 1:1 sex ratio is less efficient than one in which there are just enough males so that every female is fertilized. It is difficult to see how such a gene could be selected for on this basis, unless group selection is operating, and that seems most unlikely since the breeding populations in nature are probably of the order of several hundred individuals.

It is also possible that SR is linked to some other gene or constellation of genes which are selectively advantageous. It is probably significant that all the SR genes which have been studied cytologically are associated with inverted segments of the chromosome. However, the nature of the associated genes, if they exist, is a complete mystery. It is in fact not clear why any gene arrangement which is selectively advantageous should have to carry with it a pleiotropic effect such as SR, unless SR is really selectively neutral.

Another possibility is that SR/ST females have some advantage over ST/ST females, and that this is sufficient to maintain a balanced polymorphism in the population. Studies by Wallace (1948) and Prakash and Merritt (1972) indicate that physiological differences are associated with different combinations of SR and ST chromosomes. Unfortunately the

direction and magnitude these differences take in nature is almost impossible to determine. Data on genotype frequencies (table 1) suggest that SR/SR females in nature do not have the very low fitness that Wallace found in the laboratory, but if the low fitness were less extreme than that found by Wallace (about 0.02 at 25° C; about 0.31 at 16.5° C), it could escape detection by a method of such low resolution. An additional source of uncertainty is our almost complete ignorance of what happens to *D. pseudoobscura* larvae in nature.

A fourth possibility is that an SR male produces slightly more female progeny than does an ST male. The mechanism for this could be in the production of sperm, the viability of the sperm, mating success, or some other possibility. In the brooding experiment described above SR males in fact produced about 8% more female progeny than ST males (table 2). If such an advantage obtains in nature, it would mean that SR is in fact meiotically driven, but relatively gently; instead of the 100% advantage it has been thought to have, the advantage would be less than 10%. Although such an advantage is so small as to be almost impossible to detect by sampling natural populations, it would be extremely large in evolutionary terms.

With the present information available I am inclined toward the last explanation, but none of the possibilities can be ruled out, even if they are distasteful.

SUMMARY

"Sex ratio" (SR) is a widespread genetic condition of the X-chromosome in *Drosophila* species which causes males to produce progenies consisting almost entirely of females. Results of samples from natural populations of *Drosophila pseudoobscura* and results of some laboratory experiments indicate that SR males produce only about half as many sperm as normal (ST) males; because of this deficiency, SR males are able to fertilize only about half as many eggs as ST males. These results explain the observed equilibria of frequencies of SR in natural populations, and suggest that, at least in the case of *D. pseudoobscura*, male fertility may be partly limited by the number of sperm males can produce.

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APPENDIX

The method of determining the genotypes of females by testing some of their sons, although used by Sturtevant and Dobzhansky (1936), was not correctly inter-

puted by them. The problem is deciding whether, if some number of the male progeny of a female are tested and all are found to have the SR chromosome, the female was SR/SR or SR/ST. Sturtevant and Dobzhansky assumed that "if three or more like sons were found . . . both of the X's of the mother were tested."

Assuming the frequency of SR/SR homozygotes to be the square of the frequency of the SR gene in females (i.e., that the population is in Hardy-Weinberg equilibrium for SR), the following calculations may be made. If the gene frequency of SR is 20% (this is close to observed frequencies; see table 1), then 4% of all females will be SR/SR, 64% will be ST/ST, and the remaining 32% will be SR/ST. The problem, properly stated, is: if a female is drawn at random from this population and an X-chromosome is chosen at random from her seven times (i.e., seven of her sons are tested as described in text), supposing that all seven are SR, what is the probability that this female is in fact homozygous for SR?

If an X-chromosome is chosen at random seven times from a fly which is in fact SR/SR, the probability of getting seven SR chromosomes is 100%. If the female is heterozygous, the chance of getting seven SR chromosomes is $1/128$. A heterozygote is eight times as likely to be chosen as an SR/SR homozygote, since 32% of the females are SR/ST but only 4% are SR/SR. Thus if all seven sons of one female are SR, she is either an SR/SR homozygote with a 4% chance of being chosen but a 100% chance of producing seven SR sons, or she is a heterozygote with a 32% chance of being chosen and a $1/128$ chance of producing seven SR sons. The probability that the female is SR/SR is thus 16 times as great as the probability that she is heterozygous. Since the probabilities sum to 1.00, the probability that she is SR/SR is $16/17$ or 94%. If only three sons were tested and all three were SR, their mother would be as likely to be SR/ST as she would to be SR/SR.

In the case where the frequency of SR is 16% (below the lowest frequency I found; table 1) a female producing seven SR sons has a probability of 92% of being SR/SR. Thus, if the assumption of Hardy-Weinberg equilibrium holds, the estimates of the frequencies of SR/SR homozygotes are quite reliable; those for ST/ST homozygotes are very reliable.

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