DISTRIBUTIVE PAIRING OF COMPOUND CHROMOSOMES IN FEMALES OF DROSOPHILA MELANOGASTER

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THE relation between crossing-over and disjunction in the Drosophila female has been studied for many years. ANDERSON (1929), DOBZHANSKY (1932, 1933), BROWN (1940), PIPKIN (1940) and others clearly demonstrated that crossing-over has a strong influence on disjunction in translocation heterozygotes. The reciprocal products of an exchange tend to pass to opposite poles of the first meiotic division spindle. On the other hand, COOPER (1945) stressed that normal segregation can occur without crossing-over and strongly contradicted the hypothesis of DARLINGTON (1929) that chromosome pairs not oriented by a chiasma (the cytological manifestation of a crossover) do not regularly segregate one member to each pole of the spindle.

The discoveries of highly nonrandom assortment of nonhomologous chromosomes by R. F. GRELL (1957, 1959) and OKSALA (1958) have provided new methods by which the interrelation of crossing-over and disjunction can be reanalyzed. Such an analysis led R. F. GRELL (1962a, b) to a new hypothesis of the nature and sequence of some of the events of meiosis in oocytes of *Drosophila melanogaster*. The most novel feature of her hypothesis is that meiosis is postulated to contain two distinct types of chromosome pairing. The first pairing is called *exchange pairing* and is between homologous loci, prior to and necessary for crossing-over. The second is *distributive pairing* which occurs after crossing-over. This second pairing may involve either homologous or nonhomologous chromosomes. It occurs before the meiotic anaphase so that two chromosomes thus paired will pass to opposite poles of the division spindle. All co-oriented pairs of chromosomes are probably involved in distributive pairing, but distributive pairing becomes evident as separate from exchange pairing only in certain situations of nonrandom assortment of nonhomologous chromosomes or in secondary nondisjunction.

In general, a chromosome that has been involved in a crossover event with its homologue will pair distributively with its homologue. A chromosome that has not been involved in an exchange with its homologue may participate in nonhomologous distributive pairing. In the case of the X chromosomes, the same conditions that will allow nonhomologous distributive pairing will also allow distributive pairing with the Y chromosome. Therefore, as demonstrated by BRIDGES (1916) the two maternal X chromosomes in secondary exceptions from XXY mothers are noncrossovers. Similarly, ROBERTS (1962) showed that exceptions resulting

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from nonhomologous pairing of X's and autosomes invariably had two noncrossover X chromosomes.

An important part of the hypothesis is that noncrossovers are *not* the consequence of nonhomologous pairing, nor are noncrossover X's in secondary exceptions produced by X-Y pairing. Nonhomologous pairing, as revealed by nonrandom assortment, is between chromosomes which are noncrossovers even though they had the opportunity of crossing over with their respective homologues at exchange pairing. In other words, the absence of an exchange is a prerequisite for and not a result of nonhomologous pairing. The essential features of the meiosis proposed by R. F. GRELL are diagrammed in Figure 1.

This hypothesis did not originally consider the behavior of so-called "compound chromosomes." These are chromosomes formed by the joining of two homologous chromosome arms onto one centromere. The first and most familiar compound chromosome was the attached-X (reversed metacentric, in the descriptive terminology of NOVITSKI 1954). Another example of a compound X chromosome is the reversed acrocentric (RA).

If a compound chromosome becomes involved in nonhomologous pairing, it is possible, at one extreme, that crossovers between elements of the compound prevent that chromosome from participating in nonhomologous pairing, as reported by R. F. GRELL for noncompound chromosomes. At the other extreme is the possibility that crossing-over within the compound has no effect on its nonhomologous associations. These two possibilities are diagrammed in Figure 2. The data presented in this paper indicate that the latter alternative (Figure 2, part A) is the true situation, and that crossing-over within the compound has no effect on non-

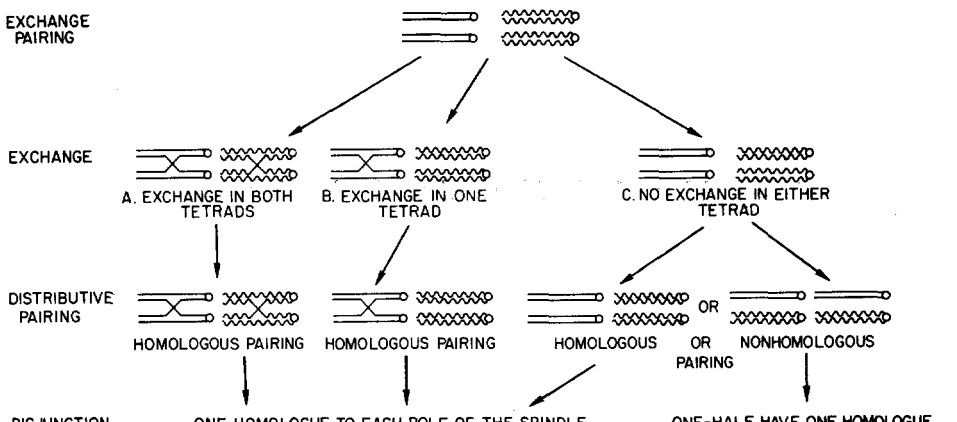

FIGURE 1.—Scheme of first meiotic division according to hypothesis of R. F. GRELL (1962a, b). Crossovers cannot become involved in nonhomologous pairing. If only one pair is noncrossover, it has no alternative except to pair homologously at distributive pairing. If two pairs are noncrossovers, there is a possibility of nonhomologous distributive pairing.

random assortment between the compound chromosome and nonhomologous chromosomes.

RAMEL (1958) investigated nonhomologous pairing of an attached-X with autosomes. He found that heterozygous autosomal inversions increase the frequency of nondisjunction of an attached-X and a Y. Furthermore, females carrying an attached-X and heterozygous autosomal inversions but no Y chromosome produce more dominant-lethal eggs than those with a Y. The latter observation was interpreted as an indication that an attached-X in the absence of the Y chromosome causes more autosomal nondisjunction than occurs when both attached-X and Y are present and may pair with each other.

Later, RAMEL (1962) developed a technique of recovering a proportion of eggs with two second chromosomes by mating test females to irradiated males. The irradiation occasionally deletes a second chromosome from a male gamete. When a nullo-2 sperm fertilizes a diplo-2 egg, a viable zygote is produced. The frequency of exceptions with two maternal second chromosomes was higher from attached-X females without a Y than those with a Y. Furthermore, from mothers without a Y, all exceptions were males. This indicated to RAMEL that the attached-X and a second chromosome had paired nonhomologously and passed to opposite poles of the first meiotic division spindle; thus, diplo-2 eggs would not receive the attached-X.

RAMEL (1962) found that crossing-over is higher in attached-X females with no Y when heterozygous autosomal inversions are present than when no inversions are present. Exchange in an attached-X is increased by the interchromosomal effect of heterozygous inversions in spite of frequent nonhomologous pair-

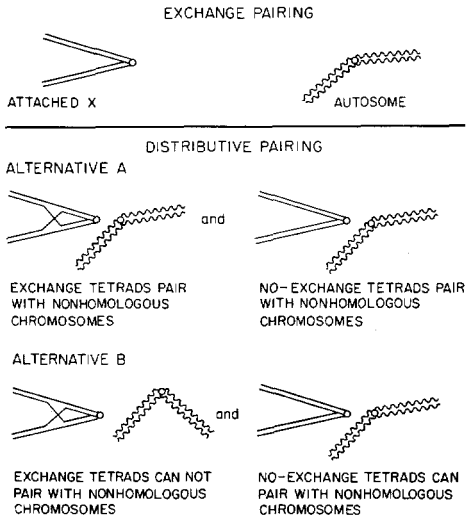

FIGURE 2.—The possible effect of exchange on nonhomologous distributive pairing of compound chromosomes.

ing between the attached-X and autosomes. He concluded that the centromere, as the only single element of the attached-X, is the likely site of nonhomologous pairing.

The results presented below are consistent with those of RAMEL and are fit into the distributive pairing hypothesis of R. F. GRELL.

MATERIALS AND METHODS

The chromosomal rearrangements and mutants used in experiments are listed and briefly described in Table 1.

The methods of culture were carefully controlled. Female flies were selected as virgins less than eight hours after eclosion from the puparia. They were mated singly to three males in vials. After mating in vials for a period of from 12 to 24 hours, the flies were transferred to quarter-pint bottles containing a corn meal-agar-sugar-brewer's yeast medium. The parents were removed from the bottles on the sixth day. The cultures were kept in a constant environment room at 25°C and 70 percent relative humidity.

EXPERIMENTS AND RESULTS

The first point examined was the extent of compound chromosome participation in nonhomologous pairing (i.e., distributive pairing with a nonhomologous chromosome). For this purpose, several kinds of females were constructed. Each was heterozygous for T(2;3)A, *Bl*/SM1, *Cy* and carried one of the following compound X chromosomes: RM, *pn*, RM, *In (1)65*, *y*, RM, *In(1)dl-49*, *v f*, RA or RA·Y^L. These females carried no free Y chromosome. The 2,3 translocation-inversion system was used originally by OKSALA (1958) to demonstrate nonrandom assortment of autosomes and a Y chromosome. A similar translocation-inversion system was used by FORBES (1960) to induce high rates of primary nondisjunction of structurally heterozygous X chromosomes. FORBES demonstrated that the autosomes assorted very non-randomly among the X-chromosome exceptions. The action of the inversion-translocation complex is explained in terms of the hypothesis of R. F. GRELL in Figure 3.

The second chromosome (SM1) is free to pair with the compound X's and a high degree of nonrandom assortment occurs between them (Table 2). The most frequent types of progeny, therefore, are those that derive a compound X or a SM1, *Cy* chromosome from their mother and are consequently T(2;3)A, *Bl* females or SM1, *Cy* males. The less frequent types receive neither or both of these two chromosomes from their mother and are SM1, *Cy* females and T(2;3)A, *Bl* males.

With the reversed metacentric, RM, *pn*/0; T(2;3)A, *Bl*/SM1, *Cy*, 0.90 of the progeny were females with T(2;3)A or males with SM1. The corresponding proportion for RM, *In(1)65* and RM, *In(1)dl-49* were 0.88 and 0.86 respectively. With RA as the compound X the frequency was 0.75, and with RA·Y^L it was 0.79. These may be termed segregation frequencies between the compound X chromosomes and SM1, *Cy*. The pairing frequencies may be calculated by assuming that

TABLE 1

Mutants and chromosomal rearrangements used in experiments

Chromosome symbol	Description	Reference
RM, *pn*	Attached-X chromosome with prune homozygous	
RM, *In(1)65, y*	Attached-X homozygous for *In(1)65* with yellow	
In(1)65	Inversion of X chromosome; breaks at 1C and 10B on salivary chromosome map	LINDSLEY, EDINGTON, and VON HALLE (1960)
RM, y^2 *sc* w^a *ec* · *In(1)65,y*	Attached-X heterozygous for a normal sequence arm and *In(1)65* with listed markers	
RM, *In(1)dl-49, v f*	Attached-X homozygous for *In(1)dl-49* marked with *v* and *f*	
In(1)dl-49	Inversion in X chromosome; breaks at 4DE and 11F	BRIDGES and BREHME (1944)
RM, y^2 *sc* w^a *ec* · *In(1)dl-49, v f*	Attached-X heterozygous for normal sequence and *In(1)dl-49* with markers listed	
RA	Reversed acrocentric compound X	
RA · Y^L	Reversed acrocentric compound X with the long arm of the Y chromosome as a second arm	
B^SY	A Y chromosome marked with B^S	BROSSEAU, NICOLETTI, GRELL and LINDSLEY (1960)
T(2;3)A,*Bl*	Reciprocal translocation between chromosomes 2 and 3. Break points at 39BC and 83B. Marked with inseparable dominant, Bristle	E. B. LEWIS (1951)
SM1, *Cy*	Six-break rearrangement of chromosome 2 ("second multiple 1")	LEWIS and MISLOVE (1953)
Attached-4	Two fourth-chromosomes attached to a centromere	E. B. LEWIS and A. ROBERTS (unpublished)

The following mutants were used: *y* and y^2: yellow body color (1–0.0); *sc*: scute bristles (1–0.0); *pn*: prune eye color (1–1.0); w^a: apricot eye color (1–1.5); *ec*: echinus eyes (1–5.5); *v*: vermilion eye color (1–33.0); *f*: forked bristles (1–56.7); *Bl*: Bristle (2–54.8); *Cy*: Curly wings (2–).

when the chromosomes are not paired, segregation is random and there is a proportion of the gametes that show segregation, but did not pair. An equal proportion fail to show segregation. The frequency of pairing, $a = 1 - 2n$, were n is the frequency that fails to segregate (GRELL and GRELL 1960). The values of a for

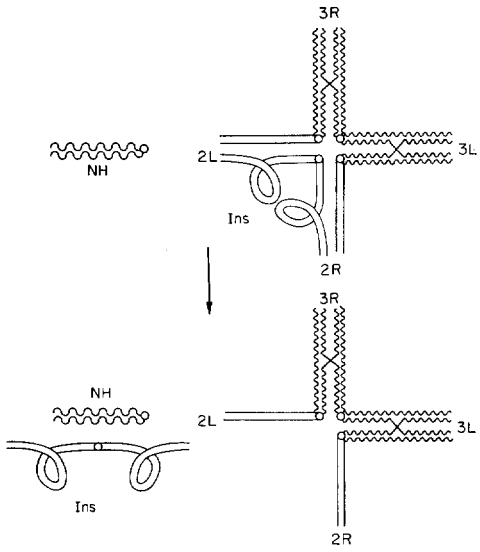

FIGURE 3.—The use of a translocation and inversion to induce nonhomologous distributive pairing. 2L, 2R, 3L and 3R are the left and right arms of the second chromosome and the left and right arms of the third chromosome. Ins is a chromosome with inversions in both 2L and 2R and is a noncrossover. NH is nonhomologous to the second chromosome and is also a noncrossover. There is a high probability of crossovers in both 3L and 3R which prevent the translocation and normal third chromosome from nonhomologous distributive pairing and keeps them together in a three-member complex. The inversion chromosome (Ins) and the nonhomologous chromosome (NH) will then pair at distributive pairing and disjoin to opposite poles of the first meiotic spindle.

the compound X's and SM1 are 0.80, 0.76, 0.72, 0.50 and 0.58 for RM,*pn*, RM,*In(1)65*, RM,*In(1)dl-49*, RA and RA·Y^L respectively.

To demonstrate that the high values of segregation are not artifacts of viability, crosses were made in which the T(2;3)A was derived from the female parent and SM1 from the male. As shown in Table 3, there is no evidence of consistent inequalities in classes except between total males and total females. It appears that the compound X's or markers on them are somewhat inviable.

In a second set of experiments, nonrandom assortment between the compound fourth chromosome (LEWIS and A. ROBERTS unpublished) and a Y, a second chromosome or an attached-X was studied. The attached-4 and a Y chromosome segregate to opposite poles with a frequency of 0.988; the attached-4 and SM1 segregate with a frequency of 0.95 (Table 4). Finally, if the attached-4 and attached-X are in the same primary oocyte and both are without homologues, they pass to opposite poles with a frequency of 0.97. The pairing frequencies (a) are calculated to be 0.976, 0.90 and 0.94 between the attached-4 and Y, attached-4 and SM1 and attached-4 and attached-X, respectively.

That both crossover and noncrossover attached-X chromosomes pair nonhomologously with SM1 to about the same extent may be demonstrated with attached-X's that are heterozygous for markers. Crossing-over leads to homozygosity of

TABLE 2

Nonrandom assortment of compound X chromosomes and SM1, Cy

Female parent	Progeny				n*
	XX; T(2;3)A	XX; SM1	T(2;3)A	SM1	
RM, *pn*/0; T(2;3)A/SM1	498	71	56	771	0.90
RM, *In(1)65, y*/0; T(2;3)A/SM1	166	24	43	325	0.88
RM, *In(1)dl-49, v f*/0; T(2;3)A/SM1	406	74	74	522	0.86
RA/0; T(2;3)A/SM1	131	84	166	617	0.75
RA · Y^L/0; T(2;3)A/SM1	108	23	69	246	0.79

* The segregation frequency, $n = \frac{\text{XX; T(2;3)A + SM1}}{\text{Total of progeny}}$

TABLE 3

Progeny without nonrandom assortment when T(2;3)A and SM1 from different parents

Female parent	Male parent	Progeny								n_a*
		RM; T(2;3)/+	RM; SM1/+	RM; T(2;3)/SM1	RM; +/+	T(2;3)/+	SM1/+	T(2;3)/SM1	+/+	
RM, *pn*/0; SM/+	T(2;3)/+	84	104	65	89	158	161	135	155	0.48
RM, *In(1)65, y*/0; SM1/+	T(2;3)/+	69	53	59	67	101	137	116	105	0.57

* $n_a = \frac{\text{XX; T(2;3) + SM1}}{\text{XX; T(2;3 + SM1 + XX; SM1 + T(2;3)}}$

TABLE 4

Nonrandom assortment of the attached fourth chromosome

Female parent		Progeny				*n*
		+; A–4	+/B^SY; A–4	+; 0 (haplo-4)	+/B^SY; 0 (haplo-4)	
+/+/B^SY; A–4/0	females	676	2	8	194	0.988*
	males	616	13	3	270	
		T(3;4); A–4	SM1; A–4	T(2;3); 0 (haplo-4)	SM1; 0 (haplo-4)	
SM1/T(2;3)A; A–4/0	females	643	24	1	12	0.95*
	males	635	42	10	107	
		0; A–4	RM; A–4	0;0 (haplo-4)	RM; 0 (haplo-4)	
RM, *pn*/0; A–4/0		618	18	7	63	0.97*

* Based on non-haplo-4's.

TABLE 5

Nonrandom assortment of recombinant and nonrecombinant compound X chromosomes

Female parent	Progeny						*n* (recom) female	*n* (nonrecom) female
	nonrecom T(2;3)	recom T(2;3)	nonrecom SM1	recom SM1	T(2;3) male	SM1 male		
RM, y^2 *sc* w^a *ec* · *In(1)65*, *y*/0; SM1/T(2;3)A	648	128	134	41	250	1552	0.76	0.83
RM, y^2 *sc* w^a *ec* · *In(1)dl-49 v f*/0; SM1/T(2;3)A	409	65	112	18	110	529	0.78	0.79

markers in either arm which can be detected. If the attached-X is also heterozygous for an inversion, the amount of exchange is reduced and the analysis more straightforward. For this purpose attached-X's of two kinds were produced. One carried *In(1)65*, *y* on one arm and y^2 *sc* w^a *ec* on the other arm. The second attached-X carried *In(1)dl-49*, v^{0f} *f* and y^2 *sc* w^a *ec*. These inversions are in the distal half of the chromosome so that, for practical purposes, the only recombinants are those between the centromere and the proximal break point of the inversion. These attached-X's were combined with T(2;3)A, *Bl*/SM1, *Cy* and the females were mated to Canton-S males. The progeny are recorded in Table 5. The female progeny have been divided into recombinant and nonrecombinant classes. The recombinant class were those homozygous for markers on either arm of the maternal attached-X. One half of the exchange tetrads do not give rise to homozygosis and are represented in the nonrecombinant class.

Table 5 shows that in the attached-X and SM1 both the recombinant and nonrecombinant classes are nonrandomly assorted. In mothers heterozygous for *In (1)65*, *y*, the attached X and SM1 passed to opposite poles with a frequency of 0.83 in the nonrecombinant class and 0.76 in the recombinant class. When *In(1) dl-49*, *v f* was heterozygous, the attached-X and SM1 passed to opposite poles with a frequency of 0.78 in the recombinant and 0.79 in the nonrecombinant classes. One can conclude that exchange within a compound chromosome does not affect its ability to engage in nonhomologous distributive pairing.

A control experiment was performed for the attached-X heterozygous for *In (1)65*. SM1 was introduced from the female, but T(2;3)A, *Bl* from the male. These results are recorded in Table 6. The grossly unequal classes that are characteristic of nonrandom assortment were not observed.

Attached-X females generally carry a Y chromosome derived from their male parent. This Y chromosome and the attached-X regularly segregate to opposite poles of the meiotic division spindle. The data in Table 7 illustrate the increase in nondisjunction between an attached-X and a Y with autosomal rearrangements. The *pn*/B^SY females show nondisjunction of the attached-X and the marked Y with a frequency of 0.001. Introduction of heterozygous T(2;3)A increases X, Y nondisjunction to 0.014, and with heterozygous SM1 it is 0.036. This is analogous

TABLE 6

Assortment of recombinant and nonrecombinant compound X's when SM1 and T(2;3)A are from different parents

(RM, y^2 *sc* w^a *ec* · *In(1)65*, *y*; SM1/+ ♀ × T(2;3)/SM1 ♂)

Progeny	Females		Males
	Nonrecombinant	Recombinant	
T(2;3)/+	81	35	168
SM1/+	76	23	178
T(2;3)/SM1	68	12	169
+/+	83	25	159
n_a	51.6	0.60	...

TABLE 7

Effect of autosomal rearrangements on attached-X ⟷ Y segregation

Female parent	Regular progeny		Nondisjunctional progeny		Detachments	Percentage of nondisjunction
	RM	B^sY	RM/B^sY	0		
RM, *pn*/B^sY	2796	3127	3	3	4	0.1
RM, /B^sY; T(2;3)A/+	748	685	7	13	1	1.4
RM/B^sY; SM1/+	2377	1321	73	65	2	3.6

to the effect of heterozygous autosomal rearrangements on primary nondisjunction of two free X chromosomes that was studied by COOPER, ZIMMERING and KRIVSHENKO (1955) and attributed by them to nonhomologous association.

If the attached-X females with a marked Y contain both T(2;3)A and SM1 (Table 8) the amount of nondisjunction of the attached-X and the Y increases to 0.13 when the attached X is *pn*, 0.15 when it is *In(1)65* and 0.18 when it is heterozygous for *In(1)65*, *y* and *y*^{2} *sc* *w*^{a} *ec*. In these progenies nonrandom assortment is observed, and the nondisjunctional female progeny receive predominantly the T(2;3)A, *Bl* and the nondisjunctional male progeny receive predominantly the SM1 chromosome. Pairing has occurred between the X and SM1 or Y and SM1 so that the attached-X and the Y sometimes pass to the same pole. The data from the heterozygous attached-X give no indication that recombinants and nonrecombinants were involved to different extents.

DISCUSSION

A. *Relation between nonhomologous distributive pairing and attached-X and Y segregation:* The situation in which an attached-X, a Y and SM1 are all avail-

TABLE 8

Nondisjunction of attached-X and Y with nonrandom assortment of a second chromosome

Progeny	RM, *pn*/B^sY; T(2;3)A/SM1	RM, *In(1)65,y*/B^sY; T(2;3)A/SM1	RM, *y*^{2} *sc* *w*^{a} *ec* : *In(1)65*, *y*/B^sY;T(2;3)A/SM1		
			Nonrecom	Recom	Males
Regular					
RM; SM1	411	42	195	34	...
RM; T(2;3)	334	31	140	16	...
B^sY; SM1	353	68	...	..	322
B^sY; T(2;3)	383	50	...	..	380
Nondisjunctional					
RM/B^sY; SM1	2	0	0	0	...
RM/B^sY; T(2;3)	45	4	23	2	...
0; SM1	174	21	...	..	153
0; T(2;3)	8	0	...	..	4
Percentage*	13%	15%	...	..	18%

* Calculated from males only.

able (Table 8) is one involving competition in distributive pairing. All three elements may pair since they are noncrossovers with other elements, but there is a preference of the X and Y to go to opposite poles, even though the SM1 can interfere with this process to the extent that 13 to 18 percent of the gametes received both or neither of the sex chromosomes. It is suggested that the regular segregation of attached-X and Y that is observed when other elements are also normal is due to distributive pairing, which is not basically different from nonhomologous pairing. Since normally the large autosomes are usually crossovers, they are not available for nonhomologous pairing and do not interfere with X-Y segregation.

B. *The site and control of distributive pairing:* Since compound and noncompound chromosomes behave somewhat differently, an examination of the differences between the two kinds of chromosomes should give some information as to the requirements for distributive pairing. One obvious difference is that in compound chromosomes both arms are attached to the same centromere. The data are not inconsistent with the interpretation of RAMEL (1962) that centromeres that are not paired homologously can pair nonhomologously. In noncompound chromosomes a crossover might cause the two homologous centromeres to be irreversibly paired, but a crossover within a compound could not alter the unpaired condition of the centromere.

There are some difficulties with the hypothesis of centromere pairing. It is not evident how centromere pairing would give the disjunction from a trivalent proposed by COOPER (1948) to account for more than 50 percent XX $\longleftrightarrow$ Y segregation in females heterozygous for X-chromosome inversions and carrying a Y chromosome. There is also evidence of preferential assortment in which a deleted X chromosome tended to go to one pole, and both a third chromosome fragment on a fourth chromosome centromere and a normal fourth chromosome tended to go to the other pole (GRELL and GRELL 1960).

It was also shown (GRELL and GRELL 1960) that the centromeres do not possess the specificity that may be exhibited in nonhomologous pairing. When a Y chromosome, a normal fourth chromosome and the translocated fragment of a third chromosome on a fourth-chromosome centromere are all available for pairing, the Y and the fragment on a fourth centromere segregated to opposite poles and the normal fourth chromosome segregated randomly. In other experiments it was shown that the fourth chromosome and the Y segregated very regularly to opposite poles when the translocated fragment was not available. Likewise, the fourth chromosome and the fragment segregated regularly to opposite poles when the Y was not present. When the three elements are in competition for pairing, the two elements with fourth-chromosome centromeres are not the two that go to opposite poles. Therefore, the specificity must reside elsewhere than in the centromeres.

LINDSLEY and NOVITSKI (1958) have shown that "centromere strength," as determined by properties of anaphase bridges, is not the attribute of the centromere, but of adjacent heterochromatin. Also CROUSE (1960) showed that the centromere of the sex chromosome of Sciara is not the controlling element for the chromosome's equational nondisjunction in secondary spermatocytes and elimi-

nation in the embryo, but rather that the controller lies in heterochromatin that is normally adjacent to the centromere. In the case of nonhomologous pairing, however, GRELL and GRELL (1960) have presented evidence that *all* of the specificity does not reside in proximal heterochromatin.

It is concluded that the centromeres are extremely important in the pairing of nonhomologous chromosomes since they are attachment points for the spindle fibers and must be oriented before chromosomes disjoin. Nevertheless, the centromeres themselves have little, if any, specificity of pairing. In competitive situations the preferences in nonhomologous pairing appear not to reside in centromeres.

SUMMARY

Compound X chromosomes and a compound fourth chromosome have been found to assort nonrandomly with nonhomologous chromosomes as well as with each other under certain conditions. The nonrandom assortment is presumed to be the consequence of nonhomologous pairing that directs chromosomes to opposite poles at the first meiotic division of the oocyte. Compound chromosomes (like the attached-X) are not saturated for this pairing by their pairing by their own doubleness.

The results are interpreted in accordance with a theory of meiosis proposed by R. F. GRELL. The nonhomologous pairing of compound chromosomes occurs at "distributive" pairing *after* crossing-over. When a Y chromosome segregates from a compound-X, it does so by the same process of "distributive" pairing. If a compound-X and a second chromosome are simultaneously available, there is competition for pairing and the X and Y frequently nondisjoin.

Crossing-over within the compound-X does not affect the nonhomologous pairing of the chromosome. This is in contrast to the behavior of noncompound chromosomes, which must be noncrossovers in order to be involved in nonhomologous distributive pairing.

LITERATURE CITED

ANDERSON, E. G., 1929 Studies on a case of high non-disjunction in *Drosophila melanogaster*. Z. Ind. Abst. Vererb. **51**: 397–441.

BRIDGES, C. B., 1916 Non-disjunction as proof of the chromosome theory of heredity. Genetics **1**: 1–52, 107–163.

BRIDGES, C. B., and E. G. ANDERSON, 1926 Crossing over in the X chromosome of triploid females of *Drosophila melanogaster*. Genetics **10**: 418–441.

BRIDGES, C. B., and K. BREHME, 1944 *The Mutants of* Drosophila melanogaster. Carnegie Inst. Wash. Publ. **552**:

BROSSEAU, G. E., B. NICOLETTI, E. H. GRELL, and D. L. LINDSLEY, 1961 Production of altered Y chromosomes bearing specific sections of the X chromosome in Drosophila. Genetics **46**: 339–346.

BROWN, M. S., 1940 The relation between chiasma formation and disjunction. Univ. Texas Publ. **4032**: 11–64.

COOPER, K. W., 1945 Normal segregation without chiasmata in female *Drosophila melanogaster*. Genetics **30**: 472–484.

1948 A new theory of secondary non-disjunction in female *Drosophila melanogaster*. Proc. Natl. Acad. Sci. U.S. **34**: 179–187.

COOPER, K. W., S. ZIMMERING, and J. KRIVSHENKO, 1955 Interchromosomal effects and segregation. Proc. Natl. Acad. Sci. U.S. **41**: 911–914.

CROUSE, H., 1960 The controlling element in sex chromosome behavior in Sciara. Genetics **45**: 1429–1443.

DARLINGTON, C. D., 1929 Meiosis in polyploids. II. Aneuploid hyacinths. J. Genet. **21**: 17–56.

DOBZHANSKY, TH., 1932 Studies on chromosome conjugation. I. Translocations involving the second and the Y-chromosomes of *Drosophila melanogaster*. Z. Ind. Abst. Vererb. **60**: 235–286.

1933 Studies on chromosome conjugation. II. The relation between crossing-over and disjunction of chromosomes. Z. Ind. Abst. Vererb. **64**: 269–309.

FORBES, C., 1960 Non random assortment in primary nondisjunction in *Drosophila melanogaster*. Proc. Natl. Acad. Sci. U.S. 46: 222–225.

GRELL, R. F., 1957 Non random assortment of non-homologous chromosomes. (Abst.) Genetics **42**: 374.

1959 Non random assortment of non-homologous chromosomes in *Drosophila melanogaster*. Genetics **44**: 421–435.

1962a A new hypothesis on the nature and sequence of meiotic events in the female of *Drosophila melanogaster*. Proc. Natl. Acad. Sci. U.S. **48**: 165–172.

1962b The role of distributive pairing in secondary nondisjunction. Genetics **47**: 1737–1754.

GRELL, R. F., and E. H. GRELL, 1960 The behavior of nonhomologous chromosomal elements involved in nonrandom assortment in *Drosophila melanogaster*. Proc. Natl. Acad. Sci. U.S. **46**: 51–57.

LEWIS, E. B., 1951 Additions and corrections to the cytology of rearrangements. Drosophila Inform. Serv. **25**: 108–109.

LEWIS, E. B., and R. F. MISLOVE, 1953 Report of E. B. Lewis and Rhoda F. Mislove. Drosophila Inform. Serv. **27**: 57–58.

LINDSLEY, D. L., C. W. EDINGTON, and E. S. VON HALLE, 1960 Sex-linked recessive lethals in Drosophila whose expression is suppressed by the Y chromosome. Genetics **45**: 1649–1670.

LINDSLEY, D. L., and E. NOVITSKI, 1958 Localization of the genetic factors responsible for the kinetic activity of X chromosomes of *Drosophila melanogaster*. Genetics **43**: 790–798.

NOVITSKI, E., 1954 The compound X chromosomes in Drosophila. Genetics **39**: 127–140.

OKSALA, T., 1958 Chromosome pairing, crossing over, and segregation in meiosis in *Drosophila melanogaster* females. Cold Spring Harbor Symp. Quant. Biol. **23**: 197–210.

PIPKIN, S. B. 1940 Segregation and crossing over in a 2, 3 translocation in *Drosophila melanogaster*. Univ. Texas Publ. **4032**: 73–125.

RAMEL, C. 1958 Interchromosomal effects of inversions on the segregation of Y chromosomes in females. Drosophila Inform. Serv. **32**: 150–151.

1962 Interchromosomal effects of inversions in *Drosophila melanogaster*. II. Non-homologous paring and segregation. Hereditas **48**: 59–82.

ROBERTS, P. 1962 Interchromosomal effects and the relation between crossing-over and nonjunction. Genetics **47**: 1691–1710.